COTTON AGRICULTURE AND THE FUNCTION OF GRAVEL MULCH IN THE NORTHERN RIO GRANDE

by

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ABSTRACT

The site of Poshu'Owingeh was one of several ancestral Tewa villages to experience rapid growth in the 14th and 15th centuries A.D. in northern New Mexico. Recent research has proposed that this growth was one aspect of a trend characterized by nonlinear socioeconomic change produced by increasing population size and connectivity. Agriculture, commodity production, and exchange are fundamental to this model, but direct evidence for intensification is limited and no empirical data exists for the function and mechanics of the technologies which are supposed to have supported surplus production. This research addresses the problem by examining paleobotanical and soil evidence for the function of gravel mulch, a unique agricultural technology hypothesized to have supported cotton agriculture in portions of the Northern Rio Grande.

Physical soil properties and base cation ratios are used to reconstruct the irrigation effect of gravel mulch, and soil nutrient levels are measured to assess change in soil quality associated with cultivation. Fossil pollen assemblages recovered from agricultural soil layers are used to determine the mix of crops grown in gravel mulch fields. A spatial database of archaeological sites is used to reconstruct Puebloan population dynamics in the Tewa Basin. This is compared to published estimates of population growth, the timing of socioeconomic developments in the region, and climate reconstructions.

Fossil pollen concentrations indicate that cotton was the main crop grown at Poshu'Owingeh. The substantial increase in the ratio of cotton to maize and a decrease in the diversity of economic wild plant taxa at Poshu'Owingeh suggest cotton cultivation was more intensive here than other documented sites in the region. Soil analysis revealed no evidence for degradation associated with gravel mulch. Cation ratios and particle size distribution in the A

horizon suggest that gravel mulch continues to enhance subsurface water flux. I estimate that the runoff required to produce the sodium leaching observed in mulched profiles is generated by relatively intense precipitation generated by monsoon storms. Peak rates for the spatial expansion of farming populations responsible for the construction of the gravel mulch-cotton fields follows rapid population growth in the great Tewa Basin, is coincident with the intensification of regional exchange networks, and strengthening of the North American Monsoon. Given the mechanics of agricultural technology documented in this study, and hypotheses for the importance of cotton in the regional economy; it is concluded that population dynamics, climate change, and human niche construction interacted played a significant role in social change and economic expansion in the late precontact Northern Rio Grande.

INTRODUCTION

The Tewa Basin in the Northern Rio Grande region of New Mexico (Figure 1) contains abundant evidence for dryland and runoff irrigation technology. Runoff harvesting is common in traditional agriculture in arid and semi-arid regions and is seen as a low-cost infrastructural investment to cultivate marginal lands (Bruins et al. 1986; Doolittle 1984; 2000). Ubiquitous feature types include rock alignments or terraces on hillslopes and across ephemeral channels, water retention basins, and mulched fields. Lithic mulch is a broad category of agricultural technology recorded across the globe and includes rock piles, ridges of volcanic cinders, and extensive layers of rock or gravelly sand (Lightfoot 1994). This study focuses on latter type and refers to this technology as gravel mulch. Traditional gravel mulch is best recorded in northern New Mexico (Rio Chama and Galisteo Basins), Polynesia, and northern China (Bu et al. 2013; Eiselt et al. 2017; Lightfoot and Eddy 1995; Stevenson et al. 1999). Gravel mulch consists of an intentionally placed layer of gravel and sand mined from nearby natural exposures or pits. In the northern Rio Grande, gravel mulch forms lateral deposits ranging from a few square meters to hundreds of square meters and is often bordered and portioned by cobble alignments.

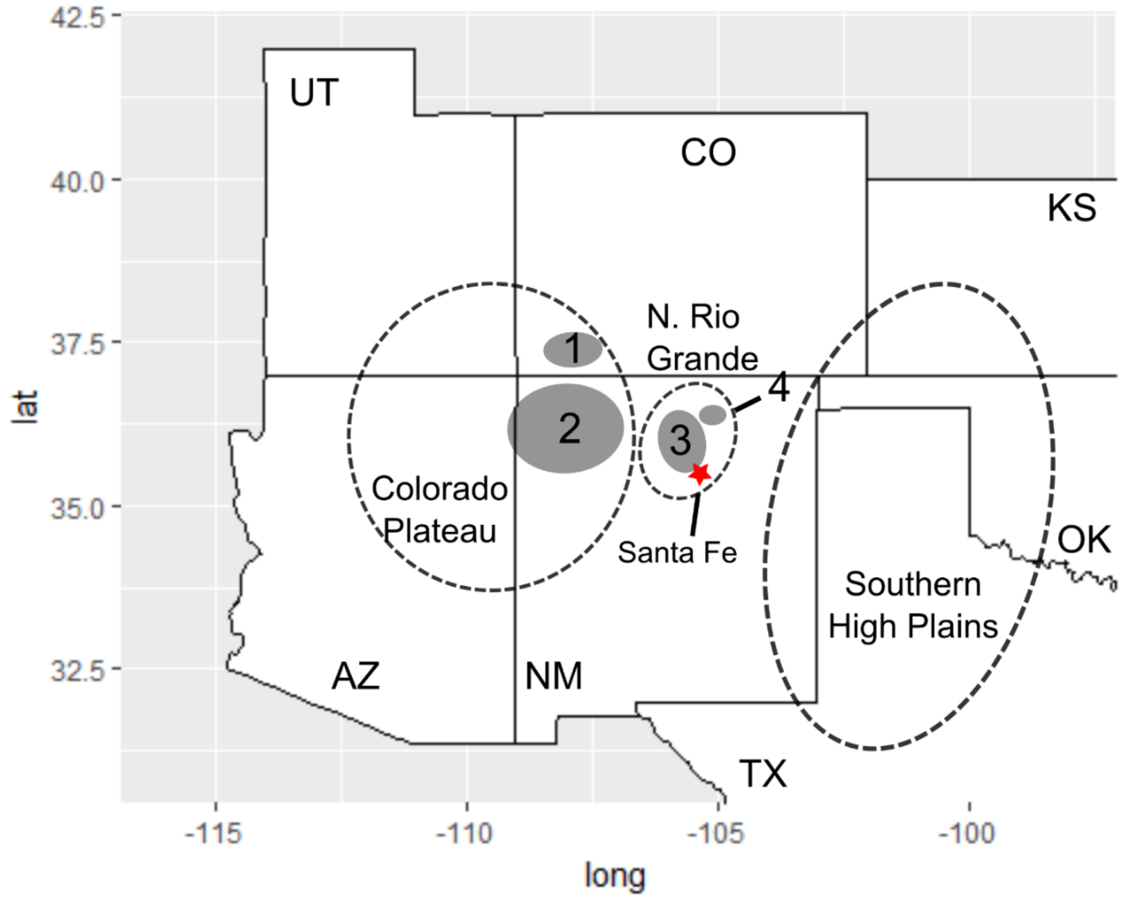

Figure 1. Regional map of the general locations discussed in the text.

That gravel mulch would develop in the Rio Chama Basin is not necessarily surprising given the marginal productivity of rainfed agriculture and the abundant supply of stratified gravel and sand in the upper Santa Fe Formation (Anschuetz 1998; Dominguez 2002; Lightfoot and Eddy 1995). One model suggests that rainfall was sufficient for maize in fewer than half the years on record (Bochinsky et al. 2016); yet the area was home to one of the largest population centers in the Southwest from A.D 1400 until the time of European contact (Hill et al. 2004). Estimates for the carrying capacity of gravel mulch fields are extremely low relative to the high population density reconstructed for the area, posing a question about the productivity of gravel mulch, what crops it was used to grow, and about less archaeologically visible fields (Eiselt et al. 2017).

Reconciling these facts – large populations in a risky environment supported by extensive agriculture – has led researchers to propose socioeconomic tactics that buffered society from the risk of resource shortfalls while explaining the historical development of Tewa social institutions. The most widely discussed models include: (1) specialized production for commodity exchange within the NRG and between the NRG and adjacent regions (Ford 1972; Habicht-Mauche 2000; Hill 1998; Snow 1991; Spielmann 1983), and (2) extensive agricultural diversification and flexible residential mobility patterns (Anschuetz 2007; Duwe and Anschuetz 2013). Recent research seeking to explain the rapid socioeconomic change observed in the area has focused attention on cotton agriculture. Specifically, growth in non-market, non-subsistence production and divisions of labor in the NRG are hypothesized to have resulted from non-linear scaling relationships with both population size and connectivity (Ortman and Davis 2019). Ortman and Davis (2019:13) demonstrate a scaling factor of ~1.17 for multiple measures of economic consumption and population size in the NRG after A.D. 1200. This suggests to the authors that agglomerative processes – increased population size, settlement density, and connectivity – produced an increasingly complex and large-scale society by the time of European contact (Lobo et al. 2019).

This overall description of socioeconomic change in the Tewa Basin is predictable from a growing literature on the role of population, technology, and social complexity; and it has considerable importance as a long-term case study. Population dynamics has become central to recent social science approaches to describing scaling relationships in complex systems and understanding the development of cultural complexity. Technological innovation and its accumulation in cultural traditions is a fundamental process in cultural evolution, but for ecosystem engineering technology; feedbacks between niche construction, carrying capacity, and population density present challenges for isolating historical factors resulting in human variability.

Non-linear scaling of various social phenomena has long been observed in urban contexts (Batty 2008; Milgram 1970) and has recently been suggested for Medieval European society (Cesaretti et al. 2016). In a cross-cultural sample, composite measures of social complexity correlate with population size, territorial area, the development of institutions that evolve along similar trajectories (Turchin et al. 2018). Recent research shows that for basic measures, cultural complexity accumulates in hunter-gatherers and agriculturalists societies at different rates, and cross-cultural variability in measures of complexity and diversity respond to different factors in the two contexts. Specifically, population size correlates positively with technological complexity in food producing societies (Collard et al. 2013; Kline and Boyd 2010), while in hunter gatherer societies environmental risk is most strongly correlated with complexity (Collard et al. 2013). One proposal for explaining this difference is that niche construction activity by food producers alters selection pressure in different ways compared to hunter gatherers (Collard et la. 2013; Fogarty and Creazan 2017). Because population size and connectivity probably affect the accumulation of complex technologies, societies will exhibit differential rates of innovation and capacity to curate knowledge within a cultural tradition (Henrich 2004; Derex and Boyd 2016). Detailed case studies of the historical expansion of agricultural societies and the trajectories of agricultural change could provide a means to evaluate this hypothesis. Geographic regions of low carrying capacity form barriers to the spatial expansion of populations and are important for explaining human cultural and genetic variability (Ackland et al. 2007). In cases were groups spread through carrying capacity barriers, climate change, environmental modification, technological innovation, and social interaction are hypothesized as enabling factors (for examples see Grollemund et al. 2015).

However, the ultimate causes of population change and the empirical relationship between agricultural technologies that underwrote commodity production and exchange, and carrying capacity are largely undocumented in the Tewa Basin. Questions persist about the distribution of cotton agriculture and its historical development, the specific ecohydrological functions of agricultural technology, and the correlation of population change with changes settlement area, connectivity, and climate. This dissertation represents a step toward this goal; an improvement in the archaeological description of functional variability in the agricultural technologies of non-industrial food producing societies. The specific objectives are to document the ways in which a specific agricultural facility alters the availability and distribution of a crucial ecosystem resource, numerate types of crops associated with this technology, and place this system in historical context for a discussion of its development and social importance.

Three papers are outlined in this introduction and presented in full in each appendix. The first provides details on the spatial spread of farming communities in the Tewa Basin after A.D. 1000 in order to discuss the role of migration and diffusion in the delayed expansion of farming villages in this region. The second paper details a geoarchaeological study on the effects of gravel mulch (an irrigation technology) on subsoil water flux and soil quality. This paper reconstructs the amount of water added to the soil root zone as a direct result of gravel mulch and shows how this technology may have been a response to the 13th and 14th century strengthening of the North American Monsoon. The third paper documents pollen evidence for cotton cultivation in gravel mulch fields. This paper finds evidence for relatively concentrated cotton production and speculates on the implications for late precontact Tewa society. Themes addressed in the papers include the role of history, movement, and diffusion in rapid population change, the empirical effects of ecosystem engineering in a non-industrial food producing society, and intensification.

Puebloan culture history in the Tewa Basin

Archaeological evidence for the extent of ancestral Tewa settlements comes from the distribution of decorated pottery with distinct pastes and room block villages ranging from hundreds to thousands of rooms in multistory blocks. The Tewa Basin is bounded roughly by Rito Frijoles Canyon on the Pajarito Plateau in the southwest corner, the Rio Tesuque in the southeast, Abiquiu Reservoir on the northwest, and the upper Ojo Caliente drainage on northeast (Figure 2). Bandelier (1892) made the first scientific ethnographic and archaeological descriptions in the area and early on linked contemporary Pueblos with the archaeological remains of the large room block villages associated with Black-on-white pottery throughout the Tewa Basin. Survey and excavations in the Tewa Basin suggested a bounded culture area within which a distinct Black-on-white ceramic lineage developed from early mineral painted wares into late precontact period wares (Hibben and Stallings 1937; Jeançon 1923; Merra 1934; Stallings 1932). Based on architectural and ceramic homogeneity across the Tewa Basin, similarities between the Black-on-white tradition in the NRG and San Juan Basin, and the general synchronicity between population increase in the NRG and decline across the Colorado Plateau. Kidder (1924, in Kidder 2000) proposed that migration accounted for the population increase into the NRG and Tewa Basin specifically. This hypothesis was supported by the finding that the vast majority of tree-ring dated structures in the Tewa Basin post-dated A.D.

1290 (Stallings 1933; Smiley et al. 1953). Subsequently, more specific models for Tewa origins were proposed involving large scale migration from Mesa Verde (Reed 1954) or development from NRG traditions with cultural exchange between migrants and autochthons (Merra 1935; Wendorf 1954; Wendorf and Reed 1955).

This issue of Tewa ethnogenesis continues to motivate considerable archaeological research in the Tewa Basin. Syntheses of the archaeological record show limited evidence for settlements in the Tewa Basin prior to about A.D. 1200 and rapid growth from the middle 13th century through the early 14th century (Crown et al. 1996; Duwe 2011; Orcutt 1999; Ortman 2012). The few sites that have been definitively dated to before A.D. 1200, and those which are, tend to be clustered in the southern-most portion of the area (Wiseman 1995; Boyer and Lakatos 2000). There is a distinct spatial trend in the founding ages of settlements across the region with Developmental sites (A.D. 900-1200) located around the Santa Fe area and south of the Pajarito Plateau, Early Coalition sites (A.D. 1200-1275) located across the Pajarito Plateau, and late Coalition – early Classic period (A.D. 1275-1400) sites founded across the entire Tewa Basin. Evidence from ceramic frequencies, tree-ring dates, and architectural patterns suggests a shift in population from the Pajarito Plateau to the Rio Chama Basin after around A.D. 1400 during the middle Classic (Duwe 2011; Kohler 2004; Preucel 1987). This was followed by a decrease in population densities in the Chama Basin, presumably due to movement into communities near the current locations of Tewa Communities from the mouth of the Chama River to the Santa Fe area. The beginning of population decline in the Chama Basin is difficult to date precisely, but tree-ring and luminescence dates on late styles of Tewa series Black-on-white wares suggest that the depopulation of the Chama Basin could have started as early as the middle 15th century and was largely complete by the middle to late 16th Century (Ramenofsky and Feathers 2002;

Robinson and Warren1971). However, uncertainty about the end dates for the manufacture of common Black-on-white (Biscuit B) and Black-on-cream (Sankawi) pottery types allows for the possibility that the area was still occupied by smaller communities either seasonally or on a semi-permanent basis through the Colonial and Pueblo Revolt periods (A.D. 1600-1700) (Ramenofsky and Feathers 2002).

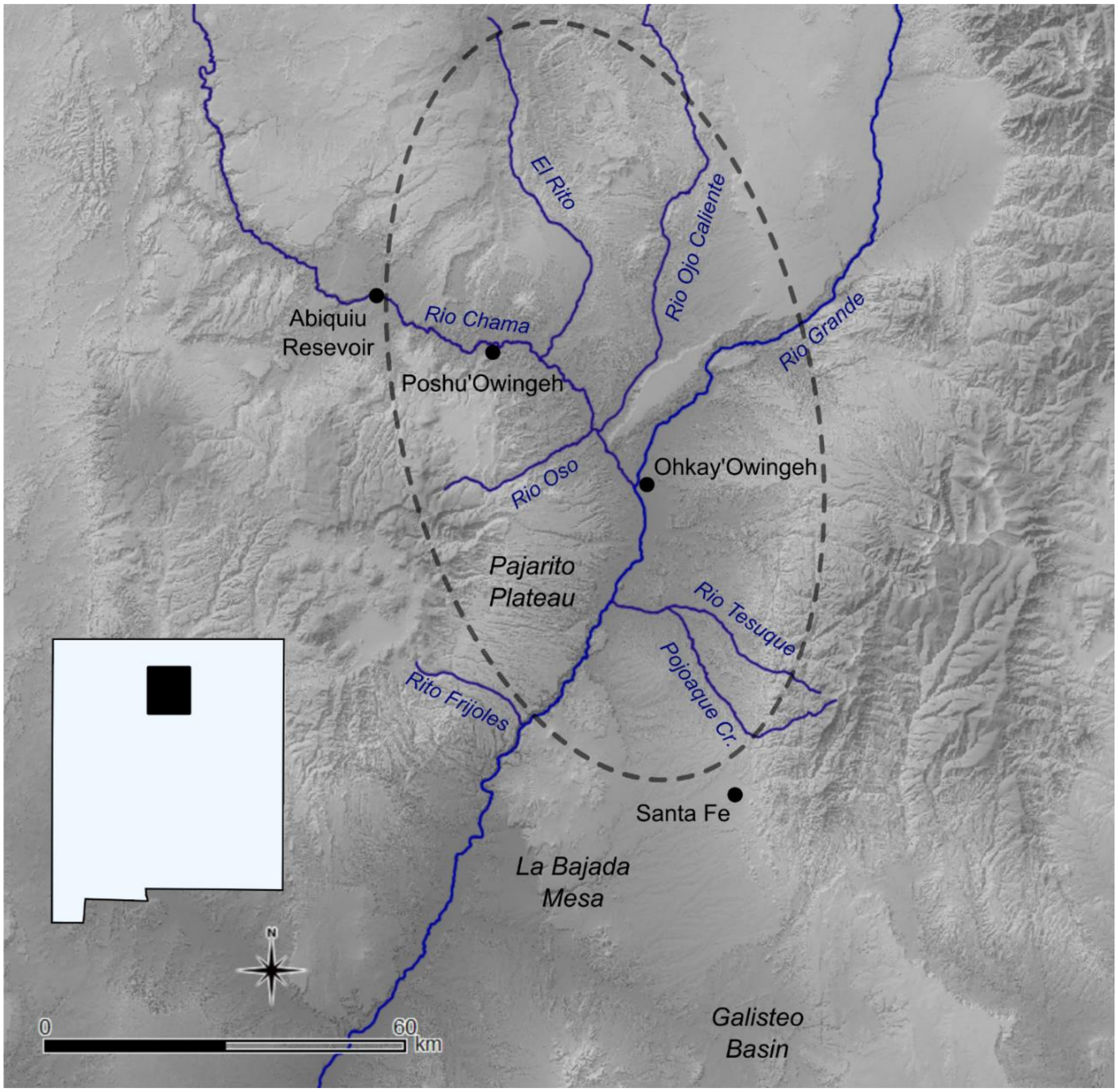

Figure 2. Overview of the Tewa Basin and locations discussed in this introduction and overview.

Material culture in the Tewa Basin is characterized by an innovative blend of Mesa Verde and late Developmental styles and patterns (Clark 2019). An early explanation for these patterns is that communities from the San Juan Basin and Mesa Verde areas migrated into the Tewa Basin during the late 13th century (Reed 1949). Accumulating evidence strongly suggests that migration from population centers in the Mesa Verde area accounts for the rapid and late appearance of room block communities in the Tewa Basin. Tewa history emphasizes population movement as a constant and recurring aspect of life (Naranjo 1995; Naranjo 2008), and some argue that place names for Mesa Verde landscape features are retained in the Tewa vocabulary (Ortman 2012). Pueblos constructed on the Pajarito Plateau in the Coalition period resemble plaza-oriented roomblocks from the San Juan Basin (Kohler 2004), and late Coalition – early Classic settlements farther north suggest rapid construction of uniform roomblocks (Duwe 2011). This pattern is consistent with expectations that migrating groups would utilize proven modular architecture (Bogucki 2003). Reconstructed population growth rates in the Tewa Basin are not compatible with intrinsic demographic growth (births and deaths). Change in architectural capacity averaged approximately 1-2 percent per year over the course of two centuries after ca. A.D. 1250, and may have been greater than 5 percent over some decades (Duwe et al. 2011; Ortman 2012; 2014). This rate is an order of magnitude higher than long-term growth rates estimated for Neolithic populations globally (ca. 0.1) and more than twice the estimated rate for the century scale population surges experienced in non-industrial food producing societies (ca. 0.5 %) (Cowgill 1975; Gignoux et al. 2011; Hassan 1978).

Alternative explanations to large-scale migration into the Tewa Basin suggest that *in situ* growth and expansion from population centers in the Santa Fe area and the southern Pajarito Plateau can account for the settlement patterns observed during the Classic period. This arguments hinges on the fact that farming settlements, with a mix of pit house and above ground room block architecture, were already present in the area by the late 10th century and argues for architectural continuity across the centuries (Lakatos 2007; Schillaci and Lakatos 2016). Others dispute the relationship between room counts and actual population sizes and inferred growth rates (Boyer et al. 2010; Maxwell 1994). Additionally, revision of manufacture dates for early pottery types in the Tewa Series could alter estimates of the antiquity of early Coalition demographic and socio-cultural change (Schillaci and Lakatos 2017).

Whatever the origins of Tewa Basin populations, the fact that the number and spatial extent of communities abruptly increased after the 13th century is indisputable. This fact has influenced anthropological models of cultural change in the Tewa Basin, models that emphasize the role of population pressure on resources and environmental risk in explanations of the unique social features observed historically in Tewa Pueblos. The study area is known ethnographically for type studies on ritual moieties, a non-kinship-based division that structures the ceremonial calendar (White 1959). In Tewa villages, moieties consist of two complementary institutions (summer and winter) that assume responsibility for and control of ritual, political, and administrative activities on a seasonal basis (Ortiz 1969). The activities and responsibilities that moieties discharge is argued to have emerged due to the need to sustain large, rapidly growing, populations in a risky environment for maize agriculture (Ford 1972). Specifically, Tewa culture is hypothesized to have developed specific mechanisms – evolved from older traditions originating on the northern Colorado Plateau – to regulate periodic productive shortfalls. These include ritual redistribution, inter-pueblo and interregional alliance and exchange, increased agricultural diversity, and flexible residential patterns including a high level of mobility (Anschuetz 2007; Duwe and Anschuetz 2013; Ford 1972; Habicht-Mauche 2000; Spielman

1991). Other interpretations have emphasized the historical dimensions of the development of Tewa social institutions, particularly the moiety, over functionalist explanations, but the importance of rapid population change remains central. For example, Fowles (2005) suggests that the splitting of ritual authority was an arrangement negotiated by distinct ethnolinguistic groups in order to manage tensions created by the necessity of co-residence in the immediate aftermath of the 13th century migrations.

Puebloan agricultural technology in the NRG

For descriptive purposes, this study classifies the diversity of precontact agricultural technology documented and inferred in the NRG into four basic types based on the source and method for controlling water: direct precipitation (dryland), runoff irrigation, floodwater irrigation, and canal irrigation (Doolittle 2000). Hillslope rock alignments (inclusive of features referred to a terraces, contour terraces, and rock alignments), terraces (multi-course stacked rock walls which trap soil), rock piles, and bordered gardens (usually forming grids) have been considered direct precipitation features (Woodbury 1961; Woolsey 1986). Although these features can be extensive on the landscape, true dryland agriculture is argued to be relatively rare in the NRG because many of these features probably may have received supplemental moisture from surface runoff, springs, or seeps – all sources that may not be readily apparent to archaeologists recording such features (Anschuetz et al. 2017; Fish and Fish 1994). Linear rock alignments and grids are common in the NRG, with some of the most extensive networks observed south of the Tewa Basin, such as at La Bajada Mesa (Herhahn and Hill 1998).

Active runoff irrigation features recorded in the Tewa Basin include excavated runoff diversion ditches and water collection basins. Ditches diverting water directly onto fields and to water retention basins have been documented in field complexes around Poshu’Owingeh and contemporary Tewa Pueblos, as well as to the south in the Galisteo Basin and Albuquerque areas (Camilli et al. 2019; Crown 1987; Lightfoot 1994). One of the best documented examples of the interaction of multiple types of features in a runoff irrigated system are excavations of agricultural fields at Yungue Hills, near Ohkay'Owingeh pueblo. At this site, ditches carried water onto gravel mulch fields and into water retention basins. The intent of ditches to channelize runoff is attested to by the fact that mulched fields are buried by alluvium – they are not in an active fluvial geomorphic position – deposited by ditches after agriculture ceased.

Floodwater irrigation refers to three main technologies. The first used ephemeral channelized flow that debouched onto fields situated in alluvial fans; the second also used ephemeral flows but rather than rely on a natural gradient change at a canyon mouth, an artificial gradient change was imposed by constructing rock walls across the channel; a third method diverted overbank flow to fields situated on floodplains. The first technology is a classic farming method in the western Pueblos (Hack 1942) and was certainly used by NRG farmers (see historical references in Anschuetz et al. 2017), but its low visibility makes archaeological identification difficult. Channel walls and terraces in high gradient streams were in common use after A.D. 900 in the Mesa Verde area (Stewart and Donnelly 1943) but are less commonly identified in the NRG (though channel check dams observed in this study area of more modest scale).

Precontact canal irrigation probably did exist among the several Tanoan speaking groups south of Santa Fe to the mouth of the Rio Chama by the middle 15th century (see reviews by Anschuetz 1998; Simmons 1972). Anschuetz (1998) presents a detailed argument based on a review of Spanish accounts and archaeological data for the late development of canal irrigation from floodwater farming techniques based on rock and brush water diversions. He argues that canal irrigation was limited to water cut from perennial Rio Grande tributaries, rather than the Rio Grande itself. Eiselt et al. (2017) argue, based on the extent of runoff irrigation features and reconstructed population sizes, that canal irrigation was present in the Chama Basin, presumably by the late 14th century. Jeançon (1923) reports secondhand accounts of ditches carrying spring water to the village of Poshu'Owingeh, as well as an irrigation canal said to be of indigenous origins cutting water from Rio Chama.

Gravel mulch is the focus of this study and is one the most extensive and highly visible field types in the region. Gravel mulch consists of a layer of intentionally placed gravelly sand under which seeds were planted and functioned to increase soil water content in underlying soil layers. Agricultural experiments in field laboratories confirmed that lithic mulch enhances crop yields by (1) increasing infiltration of precipitation, (2) conserving soil moisture, (3) regulating soil temperature, and (4) mitigating soil erosion (Adams 1966; Bu et al. 2013; Corey 1968; Fairbourn 1973; Hakimi and Kachru 1978; Lamb and Chapman 1943; Li 2003; White et al. 1997; Yuan et al. 2009;). Hydrologic simulations using precontact mulched fields as model systems suggest that gravel mulch increased subsoil moisture by trapping runoff and blowing snow, increasing infiltration, and inhibiting evaporation (Dominguez 2000: 216). The mulched fields considered here differ from rock pile gardens documented in the desert foothills of Arizona and Sonora, which may also have functioned to decrease evaporation and conserve soil moisture (Fish et al. 1985). Rock piles are spatially discreet concentrations of cobbles whereas gravel mulch is characterized by rectilinear plots, with individual mulched plots measuring from 2 to 20 m^2. Through the use life of a gravel mulched field, they can expand with additions and modifications to cover as much as many tens to hundreds of square meters (Moore 2010; Anschuetz 2017; Eiselt et al. 2017).

Agricultural fields are notoriously difficult to date, and their general age is estimated based on the assumption that they are contemporaneous with nearby architectural remains and the general scatter of diagnostic ceramics. For example, gravel mulch fields from the Ojo Caliente valley were dated to after about A.D. 1360 on the basis on carful inventory of decorated sherds correlated with stratified radiocarbon dates in a midden associated with a nearby pueblo (Moore 2009). In the Rio del Oso, the earliest gravel mulched fields are inferred to date from A.D. 1275 to 1400 based on the distribution of field houses and ceramic assemblage associations (Anschuetz 1998). Based on the population history of the Tewa Basin, and the places where gravel mulch is most abundant, it appears that gravel mulch became prevalent after A.D. 1275, with peak use after A.D. 1400.

Impacts of cultivation on soil quality in the Southwest

Researchers have hypothesized that the history of land use in the Southwest represents a diverse series of fragile infrastructural intensification projects to support growing demand after changes in foraging and settlement patterns following the introduction of domesticates (Cordell and Plog 1979; Lightfoot and Plog 1984; Kohler 1992; Peeples et al. 2006). Because environmental changes directly resulting from cultivation or infrastructural intensification are difficult to observe, *cultivation legacies* – environmental variables altered by biophysical changes caused by agriculture in the past – are sought instead (Van West 2008). This is based on the observation that cultivation results in the alteration of soil properties that affect soil quality or resilience, or the ability of soils to resist threshold shifts (Cramer 2008). Information on agricultural soils is particularly relevant because inherited and humanly altered soil properties influence the trajectories of agricultural intensification (Richter 2007; Vitousek et al. 2004).

Cultivation legacies have been described in a few case studies from the Southwest, but evidence for widespread soil degradation resulting from cultivation appears to be rare in the archaeological and geological record in the Southwest (Minnis 2000; Homburg and Sandor 2011), and questions remain about the influence of precontact landscape modification and contemporary ecosystem structure and function (Fish 2000; Briggs et al. 2006). Given the agricultural diversity of the Southwest, only a small sample of infrastructure types have been studied in detail, and the available dataset is far from complete. Linear rock alignments and terraces are perhaps the best documented field types. Positive, negative, and ambiguous legacies are associated with rock alignments in the Southwest. These tend to be both the products of small changes in slope characteristics, which effect deposition and erodibility, and less frequently nutrient depletion from cultivation. For example, in southeastern New Mexico, Sandor et al. (1986) report substantially thicker A horizons behind rock alignments (runoff control features), but significantly lower organic carbon and total nitrogen. In many other cases, the effects of rock alignments are heterogeneous and difficult to discern from other processes (Homburg and Sandor 2011).

The legacies of floodwater fields tend to be more well defined than features on hillslopes. Studies on fields currently cultivated on the Zuni reservation by traditional methods, including floodwater farming on alluvial fans, suggest that runoff irrigation both provides water and sustains soil nutrient levels associated with organic matter cycling (Homburg et al. 2005; Norton et al. 2003; Norton et al. 2007). On a study of distinctly different types of precontact agricultural technologies, Hall et al. (2013) found that hillslope rock alignments were associated with no discernable changes to ecohydrological characteristics despite significantly increasing the percentage of fines, but fields designed to manage floodwater along an ephemeral channel in central Arizona were associated with predictable decreases in both particle size distribution and vegetation patterns reflecting more mesic soil conditions. Other studies have also documented changes in plant biodiversity associated with passive runoff irrigation features in central Arizona (Fish 1985; Hodgnson and Salywon 2013). This suggests that the physical soil changes and hydrology are important interacting factors controlling long-term ecosystem legacies associated with ancient agriculture in the Southwest.

Clear evidence for soil or vegetation legacies associated with gravel mulch is less common in the Southwest, a situation that leads to conflicting interpretations about the long-term effects of this technology. Lightfoot (1990; 1994; Lightfoot and Eddy 1995) proposed that the use of gravel mulch in the Galisteo Basin degraded the capacity for soil to replenish nutrients by blocking organic matter deposition. While the data to test this hypothesis was lacking, a somewhat comparable context is ridge fields in northern Arizona where volcanic ash is hypothesized to have functioned as a water conserving mulch (Elson 2011). In one study, A horizons treated with mulch were found to be substantially depleted in organic carbon (-50%) compared to unmodified locations (Berlin et al. 1977). Edwards (2007) observed a small, consistent, decline in organic matter and nitrogen, but concluded that mulch had no significant impact on soil nutrient status. Homburg and Lightfoot (2004) reported elevated organic carbon, total nitrogen, and available phosphorus associated with grid garden alignments in southeastern Arizona; hypothesized to have functioned akin to mulch by enhancing infiltration, protecting bare soil from erosion, and limiting evaporation (Fish et al. 1985; Fish and Fish 1994).

Direct evidence for irrigation functions of agricultural features

The focus on water and water management in archaeological literature on Southwest agriculture suggests that the main function of most, if not all, Puebloan agricultural technology was related to irrigation. In the NRG, most research on precontact agriculture has focused intensely on the diversity of irrigation technology in the region and explanations of its irrigation function. This is partly due to two factors, (1) the perception of the Southwest as a harsh environment for agriculture based on the fact that average annual rainfall in most locations (including Poshu'Owingeh) was probably insufficient, in and of itself, to reliably support maize agriculture (Benson 2011), and (2) the history of litigation for Pueblo water rights in the NRG (Addler 2015). Despite decades of research, very little data documents how features associated with runoff irrigation and direct precipitation fields alter soil moisture balance. There are many models, both mathematical and conceptual, in the grey literature of investigation reports by expert witnesses, but very few observations exist for soil changes caused directly by increased water flux. If direct precipitation and runoff irrigation features increased subsoil water flux, what is the soil evidence for this?

One reason for the lack of data is that some, perhaps most, agricultural technologies require constant maintenance and human intervention to remain effective. For example, massive soil degradation ensued in some instances after agricultural infrastructure was allowed to deteriorate around population centers in certain areas of Mexico (Fisher et al. 2003; Spores 1969), or at Mesa Verde (Stewart and Donnelly 1943). However, instances of vegetation and soil change highlighted in a few studies above suggest that environmental legacies do persist, and researchers are persuasive that the rock-based agricultural technologies of the Southwest caused permanent change in soil forming factors and ecohydrological conditions (Hall et al. 2013;

Sandor 2006). This study combines aspects of previous work, evaluating common measures of soil quality, with measures of water mediated soil reactions to assess more subtle changes in water flux associated with gravel mulch. The working hypothesis for the function of gravel mulch is that it transforms soil-water dynamics of the surface. Theoretically, this is the critical zone of water mediated biochemical soil reactions (Chorover et al. 2007), and water flux determines the differential depletion of soluble base ions (Chadwick and Chorover 2001; Chadwick et al. 2003). If gravel mulch indeed increases infiltration and water flux, then changes in the ratios of calcium (Ca^{2+}) (relatively resistant to leaching) and sodium (Na^{+}) (readily soluble) might be observed. Importantly, the depth of increased Na leaching under gravel mulch could provide an indication of the extent to which gravel mulch irrigation enhanced water flux.

A few previous studies have measured base ions, though for the purpose of qualifying soil fertility or quality rather than to measure change in weathering reactions. The observations of Berlin (1977) fit the hypothesis above; ash mulched ridge fields in northern Arizona were depleted in Na^{+} (-27%) compared to unmodified locations, although the authors downplay the significance of this figure. In another study from northern Arizona, Sullivan (2000) concluded that variability in the concentrations of exchangeable cations Ca^{2+}, Mg^{2+}, and K^{+} in association with linear rock alignments reflect mineral weathering conditions not affected by agricultural features. In the more arid environment of central Arizona, Nakase et al. (2014) found no change in base cations, including exchangeable Ca^{2+} and Na^{+}. Importantly, Ca^{2+}/Na^{+} ratios were similar between natural rock alignments, anthropogenic rock alignments, and soils not associated with rock alignments, and absolute concentrations of Na^{+} varied little between these treatment classes.

Pollen studies

Compared to the studies of anthropogenic changes in soil quality or evidence for the irrigation mechanism of precontact agricultural fields, pollen and macrobotanical studies are comparatively better developed in both the NRG and the greater Southwest. In general, pollen studies in the Southwest seek to quantify pollen from domesticated plants, economically useful wild species, and other plant classes in order to provide an index to field productivity, diet, agricultural diversity, and human or natural caused environmental changes (Adams 2011). This section provides an overview of selected palynological studies and results that highlight how concentrations of domesticate plants and disturbance species provide information on the function of ancient agricultural fields and patterns of land use. Pertinent studies are highlighted from Southwest as well as from relevant global contexts. A brief cultural history of two major domesticates, maize and cotton, is also summarized.

Farming in the precontact Southwest was a biodiverse endeavor, but maize (*Zea mays*) was the single most important plant. For farmers in the Puebloan tradition, it is the physical and metaphysical center of agriculture and life itself (Ford 1994). When discussing the function of runoff irrigation or direct precipitation agricultural features – a tangible description of which can be a challenge to communicate to a skeptical scientific audience – maize pollen is highlighted as a critical factor in the identification of agricultural deposits. While maize is undeniably central to precontact Southwest economies, a variety of herbs and forbs associated with disturbed soils (ruderals) are also common indicators of agricultural activity. Many of these plants were cultivated with maize, beans (*Phaseolus vulgaris*) and squash (*Cucurbita spp.*), and include bee weed (*Cleome surrlata*), *Chenopodium spp.*, grain amaranth (*Amaranthus cruentus*), mustards (*Brassicaceae spp*.), buckwheat (*Eriogonum spp.*), mallow (*Malva parviflora.*), Mormon tea

(*Ephedral torreyana*) and purslane (*Portulaca oleraceae.*) to name only a few of the economic plants commonly identified in pollen assemblages to the family or genus (Ford 1968; Nabhan 1983). Human land use in the past was associated with changes in the ratios of forested to non-forested land, reduction of woodlands, and extension of ruderal niches (Delcourt 1987). This means that classic indicators of human habitat modification are a reduction in arboreal pollen and an increase in weedy annuals (McAndrewas 1988; Mercurri et al. 2019). The latter group is dominated by *Cheno-Ams*, *Asteraceae* family, and aggregates. Some species in this taxonomic group are also economically useful and so disentangling natural successional processes on disturbed landscapes from anthropogenic encouragement – if there even is a sharp distinction – is difficult with only pollen evidence (Sullivan and Forste 2014).

Case studies from the Southwest and globally provide evidence for general patterns associated with the inception of agriculture, its intensification and decline, and the economic strategies of non-industrial food producers. For the Southwest, the first appearance of maize in local pollen records tends to be associated with simultaneous declines in arboreal taxa – *Pinus spp.* and *Juniperus spp.*, in particular – and an increase in ruderals. Changes in the concentrations and ratios of domesticates and ruderals are sensitive to the intensity of agriculture (Adams and Smith 2011), defined here as an increase in the productivity of a unit of land (concentration) and not with a total increase in productivity (Morrison 1996; Van der Veen 2005). This implies that the intensity of production of a certain domesticate can increase, increasing labor input or infrastructural development, without raising the total productivity of the agricultural system. For example, an increase in a single domesticate taxa at the expense of overall diversity of other cultivated plants does not *a priori* indicate an increase in total production but is taken to indicate an intensification in the production of that domesticate.

Pollen evidence suggests that Ancestral Puebloan farmers focused on maize production within a diversified agroecosystem that had varying impacts on natural vegetation. Maize and encouraged wild plants (particularly *Cleome surrulata*) were recovered from sediment accumulated behind rock alignments in the Mesa Verde, and a sharp increase in *Juniperus* pollen was observed in post-settlement/agricultural sediments (Martin and Byers 1965). A similar assemblage of domesticates (maize) and encouraged wild plants (*cleome*) and ruderals were found in association with hillslope rock alignments in northern Arizona, although declines in *Pinus spp.* are not as dramatic, suggesting to some that pinyon pine stands were conserved or managed (Sullivan 2000; Sullivan and Forste 2014). Berlin et al. (1977) recovered maize pollen associated with ancient ridged fields and inferred long lasting changes in the shrubland vegetation community associated with agricultural fields in northern Arizona. Maize and a variety of cultivated wild plants and ruderals were recovered from rock alignments and probable field areas in in northern Arizona in agricultural contexts dating to the 11^{th} and 12^{th} centuries (Smith 2007) Changes in the abundances and ratios of ruderals, herbs and forbs, and arboreal taxa are used to argue for subtle changes in historical land use in New Mexico (Edwards and Triggs 2016). Pollen from domesticates were not recovered from runoff irrigated hillslope rock alignments in the Sonora Desert of Arizona, but high levels of Cheno-Ams are used to argue that these features were used for agriculture (Hall et al. 2013: Online Supplement). In the Tewa Basin, maize pollen in Rio del Oso alluvium is counted in deposits dating to between 1450 and 300 B.C. which corresponds to the beginning of millennial lows in arboreal pollen (Hall and Periman 2007; Periman 2005). In Rio Oso alluvium, maize pollen becomes more common after A.D. 1000 and the period from A.D. 1000 to 1400 corresponds to peaks in disturbance taxa. Pollen evidence has helped argue for a flood diversion function for ditches in Chaco Canyon (specifically Pueblo Bonito) (Wills et al. 2016). Fossil pollen and microscopic crustaceans recovered from anthropogenic depressions show that desert Hohokam built water basins capable of long-term water storage (Bayman et al. 2004).

Globally, pollen studies have helped in the identification of agricultural features and fields and are indicative of the intensity of agriculture. Statistical groupings of pollen from domesticates, ruderals, herbs and forbs, and trees show clear associations with cultivated/disturbed and less disturbed land in Norway (Prøsch-Danielsen and Simonsen 1988). Cheno-Ams increases are documented in agricultural contexts associated with times of population increase and expansion in Precontact Argentina (Medina et al. 2017). Ratios of ruderal plant seeds are indicative of cropping regimes in an archaeological and ethnographic case study from Greece (Jones 1992). Jones et al. (2005) use detailed ethnobotanical analysis of plant functional types in different agricultural systems to show the complexity of associations between suites of agricultural weeds and cultivation strategies in a global ethnobotanical sample. A variety of cereals and weeds identified on different agricultural soils in the Netherlands helped map the extent and intensity of cultivation (Groenman-van Waateringe 1992). Cultivated plots of various ages were positively identified by the presence of cereal pollen in soil layers suspected of representing past agricultural surfaces in Sweden (Sergerström 1991). Finally, pollen records from tropical wetlands provide evidence for the timing of forest clearance and agriculture tied to population changes in the Maya lowlands (Jones 1994).

Pollen evidence suggests that the Puebloan agricultural practices changed as new communities formed in the NRG. Cotton agriculture has been suggested from pollen grains associated with gravel mulch fields in the Rio Chama Basin (Dean 1995). Recent archaeological investigations into indigenous water management technology in the NRG have recovered cotton pollen in direct association with a variety of runoff irrigated fields (Camilli et al. 2012; Anschuetz et al. 2017). Cotton pollen has been found in fields dating to A.D. 1500-1700 at the mouth of the Rio Chama and Rio Tesuque, and from fields dating to A.D.1350-1550 in the lower Rio Chama, the Ojo Caliente, and the Rio del Oso valleys (Dean 1995; Moore 2009; Smith 2008; Smith 2012). There is evidence that gravel mulch may have been more specialized in cotton production. A synthesis of pollen evidence from a variety of agricultural contexts in the Tewa Basin shows that maize and cotton are roughly evenly represented in rock alignment fields spanning the Classic period, but agricultural soil layers from gravel mulch fields in late Precontact or early historic contexts are skewed toward higher cotton pollen concentrations (Smith 2012). The highest cotton concentrations in samples from Yunge Hills are slightly more than 15 gr g^{-1}. In a survey of data across the Northern Rio Grande region, Smith (2012) reports that cotton concentrations are typically no more than 1-2 gr g^{-1} in runoff irrigated fields of all types (Smith 2012: Table 8). Not every pollen study in the NRG reports high cotton pollen, and the low number of studies leaves significant uncertainty in the extent and intensity of cotton cultivation in the NRG. Here, I address this issue while simultaneously providing data on the function of lithic mulch and the relative intensity of cotton agriculture at Poshu'Owingeh.

Dissertation overview

This dissertation surveyed the extensive gravel mulch field complex at Ancestral Tewa village of Poshu'Owingeh (LA274) to recover data related to the agricultural function for this type of field that is so common in the Chama Basin. Field work consisted of mapping approximately 4 ha of gravel mulch fields and related features, shrines, and an activity area. Pollen samples were collected from shovel text pits and soil samples from auger tests (Figure 3).

In the environmental research at Poshu'Owingeh, population dynamics in the Tewa Basin were reconstructed from a geospatial database. The purpose of this latter study was to compare the timing and rate of population expansion to social and technological change as well as to climate dynamics. This helps place gravel mulch, with its particular function and mechanics, within the context of historical change in Tewa society.

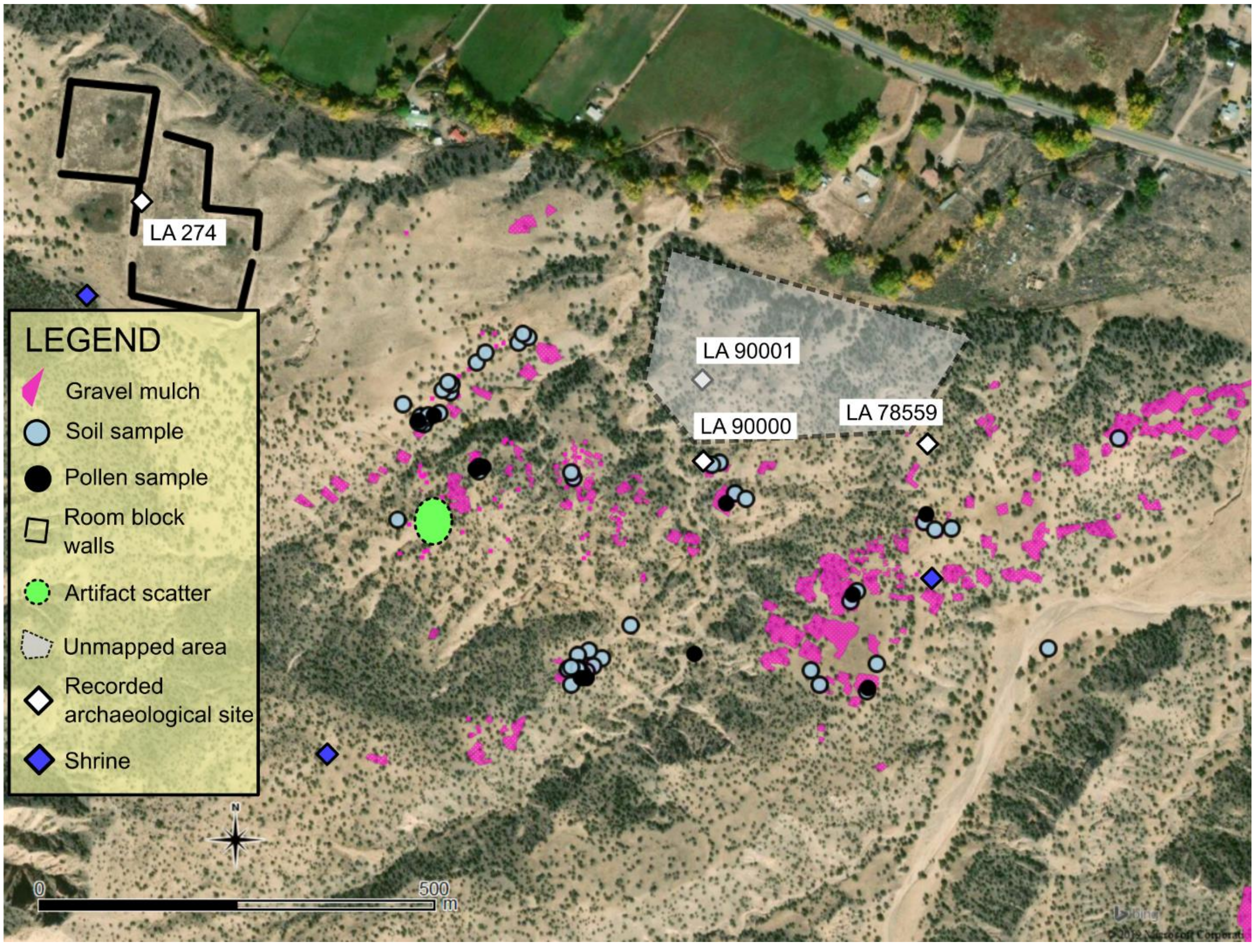

Figure 3. Locations of gravel mulch fields and samples analyzed in this study. Also depicted are recorded archaeological sites listed in Table 1, and shrines (petroglyphs, stacked rock/grinding slick, and "World Quarter"). Artifact scatter consists of a concentration of ceramics (Plain gray, Biscuit ware, and washboard micaceous), flaked and ground stone, and fire cracked rock.

Population expansion in the Tewa Basin

This article addresses an old question with a new approach. What explains the delayed expansion of agricultural communities through the Tewa Basin? To answer this question and address larger issues related to the expansion of farming, I reconstruct the rate and tempo of settlement expansion in the Tewa Basin, use this rate to make inferences about the source population, and review literature to assess how the expansion of farming settlements was contingent on population dynamics. The speed of agricultural settlement expansion is reconstructed from a network of archaeological sites across the Tewa Basin. The dataset used in this study is comprised of hundreds of observations that provide a low level of chronological detail. These low-resolution data are combined statistically to predict a continuous gridded surface of age ranks, which are calibrated with selected sites with confident ages assignments (Appendix A: Table 1, Table 2). The result is a spatially explicit estimate for the time of first arrival of agricultural villages through the Tewa Basin. The reconstructed rate of advance is then used to evaluate models of regional population history by estimating the mean dispersal distance in a reaction-diffusion equation.

The interpolation and calibration methods produced a robust reconstructed grid of the predicted “first arrival” of farming settlements in the Tewa Basin. The predicted age surface shows a clear trend in the interpolated date of grid cells increasing in a roughly radial manner from southeast to northwest (Appendix A, Figure 4). The reconstructed speed of settlement expansion is between 0.3 and 0.5 km yr $^{-1}$ (95% confidence) (Appendix A, Figure 5). Given the observed dispersal distances, a reaction-diffusion equation with generation length of 25 years and growth rate between 0.1 and 0.5 percent per year is consistent with average generational dispersal distances from 30 to 50 km per generation (Appendix A: Figure 6). This average distance is consistent with population dispersals exhibiting fat right-tails skewed by occasional long-distance migration (Auban et al. 2018; see also Bogucki 2003). Because the rate of architectural growth is so rapid in the Tewa Basin, the area *behind the wavefront* must be expanded to include regional population change including the San Juan Basin and Mesa Verde areas supporting the conclusions that regional scale population dynamics were influential in the peopling of the NRG.

Sites in the extreme southeastern portion (Rio Tesuque) and northwestern portion (Abiquiu) of the Tewa Basin are noticeably older than predicted by the spatial interpolation, suggesting that a single trend does not perfectly capture the details of settlement expansion. The modeled intercept of the dispersal speed regression fit is in the decades prior to A.D. 1200, suggesting that this is the beginning date for the main trend of settlement expansion. The most rapid period of spatial expansion, beginning in the middle 14th century A.D. post-dates peak population growth in the Tewa Basin, suggesting lags between the increase in population density and the drivers of spatial expansion.

Soil evidence for enhanced water flux below precontact gravel mulch fields in the Tewa Basin

This study seeks to contribute detailed evidence for the effects of irrigation features on infiltration and subsurface water flux and change in soil quality. I combine typical measures of soil quality in relict agricultural fields with base cation measurements of pedogenic threshold shifts to evaluate both the irrigation function of gravel mulch and address questions about its effect on soil productivity. The specific goals of this study are to (1) describe the surface subsoil horizons associated with gravel mulch to link physical soil change to functional soil properties, (2) evaluate measures of soil quality to infer the sustainability of the practice, and (3) examine reactive soils constituents to quantify the extent to which these irrigation features alter subsurface water flux.

Soil data were collected from profiles below two distinct treatments; mulched fields and unmodified locations in the immediate vicinity. A total of 125 soil samples were collected from 30 soil profiles. Profiles cluster in distinct sampling localities, which were grouped into Blocks based on soil type, vegetation characteristics, and spatial proximity (Appendix 2: Figure 2). This Block design aids in making uniform comparisons between treatment groups by controlling for nuisance variables that may affect variability independent of the treatment (Peterson 1994). Soil attributes analyzed in this study included attributes that previous research has shown to indicate changes in soil quality in agricultural features: texture, A horizon thickness, soil organic matter (SOM), total carbon (C), total nitrogen (N), available phosphorus (P_{av}), and base nutrients calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}). Also analyzed were attributes indicative of subsoil water flux that may represent a legacy of the irrigation function of gravel mulch: relative water content and exchangeable sodium (Na^{+}).

Across Blocks, no significant variability in soil quality was observed between mulched and unmodified treatments. Qualitative site factors associated with available soil moisture are positively associated with water content, SOM, and plant productivity as suggested by change in C:N and P_{av}. The data suggest that across treatments, topographic and soil variability controls plant productivity and SOM deposition to a much greater extent than mulch treatments. These data do not support the hypothesis that gravel mulch is associated with long-term soil degradation.

Significant variability in Na^{+} leaching was observed between treatments. Mulched profiles exhibited higher Ca^{2+}/Na^{+} ratios in the upper 50 cm. The depth at which Ca^{2+}/Na^{+}

equilibrates between treatments indicates the depth to which mulch increases unsaturated flow. Because texture and relative water content are controlled for, differences in unsaturated flow must result from increased water flux beneath gravel mulch. Furthermore, water flows to greater depths beneath mulched profiles in more mesic sites (~70 cm) than more xeric sites (~30 cm). A simple model system of water flux, given realistic soil parameters drawn from observations and the literature, suggests that leaching intensity beneath the average mulched profile cold be produced by the influx of a water column roughly 10 cm in height. The magnitude of irrigation required to produce Na^+ leaching to the observed depths is most compatible with precipitation events associated with the summer monsoon for three reasons: (1) soil water does not percolate significantly below the root zone in semi-arid soils, (2) water storage during winter months is primarily due to decreased evapotranspiration, and (3) renewed plant growth quickly depletes available water (Singh et al. 1998). This suggests that gravel mulch may have been specifically constructed to irrigate crops using predominantly monsoonal precipitation.

New pollen evidence for the intensity of cotton agriculture in the NRG

This paper reports on pollen assemblages recovered from various contexts of gravel mulched field complex associated with Poshu'Owingeh. The objectives were to understand what crops were grown on gravel mulched fields. The results are compared to another well documented complex of agricultural features at Yunge Hills in order to compare the intensity of agriculture at the two sites.

Pollen was collected in bulk soil samples from five categorical contexts around Poshu'Owingeh: (1) the modern surface soil (n = 2), (2) slope deposits which stratigraphically overlie an agricultural surface but are below the modern surface (n = 2), (3) agricultural soil layers in non-mulch features (n = 2), (4) directly from lithic mulch (n = 4), and (5) agricultural soil layers directly beneath gravel mulch (n = 6) (Appendix 3: Table 1). The working hypothesis guiding field sampling was that Category 1 represents the contemporary vegetation community, Category 2 represents the pre-modern vegetation community that postdates the agricultural occupation of the site, Category 3 represents the general vegetation community during the agricultural occupation, Category 4 represents the pollen rain directly on gravel mulched surfaces during and after their use, and Category 5 samples are a mixture of fossil pollen prior to mulch construction and during mulch use. After processing, fossil pollen taxa were identified by Susan Smith using standard microscopy (400x) and intensive scanning microscopy (ISM). ISM is an approach for locating rare pollen taxa in which pollen slides are scanned at 100x until a target concentration of tracer spores have been counted (Dean 1995, 1998).

Pollen preservation was excellent among the samples, with a low frequency of modern exotic pollen grains mixed in precontact agricultural contexts. ISM analysis revealed that cotton (*Gossypium hirsutum*) was recovered in 2 of 2 non-mulch agricultural contexts at concentrations around 9 gr g^{-1}, and maize was recovered in one such context at a concentration around 2 gr g^{-1}. Cotton was recovered in 3 of 4 upper mulch contexts at concentrations ranging from 18 to 81 gr g^{-1}, and maize was recovered in one such context at a concentration around 2 gr g^{-1}. Cotton was recovered in 5 of 6 lower mulch contexts at concentrations ranging from 8 to 33 gr g^{-1}. No maize pollen was recovered from lower mulch contexts (Appendix 3: Table 3). In standard microscopy, grass (*Poacae spp*.) and succulents (*Cactaceae spp*.) are comparatively rare. Pollen samples from agricultural layers tend to have higher percentages of weedy annual taxa (Cheno-Ams and *Asteraceae*) indicative of disturbance and somewhat lower percentages of native arboreal taxa pinyon pine (*Pinus edulis*), ponderosa pine (*Pinus ponderosa*), *Juniperus spp.*, *Quercus* (most likely Gambel oak *Q. gambelii*), *Abies* (most likely white fir *A. concolor*), spruce (*Piceae spp.*), and *Alnus* (most likely mountain alder *A. incana tenuifolia*)) compared to post-agricultural and modern contexts. Samples from the modern surface are lowest in weedy annuals and highest in native arboreal taxa. Buried post agricultural layers are intermediate.

The high ubiquity of cotton (83% in agricultural contexts) and multiple samples with high concentrations (25% of agricultural samples with >30 gr g^{-1}) suggest that cotton was far and away the most important crop grown in the mulched fields around Poshu'Owingeh. Comparison with Yunge Hills shows that Poshu'Owingeh cotton concentrations are indeed extremely high (Appendix 3: Figure 3). The highest cotton concentrations in samples from Yunge Hills are slightly more than 15 gr g^{-1}. In a survey of data across the Northern Rio Grande region, Smith (2012) reports that cotton concentrations are typically no more than 1-2 gr g^{-1} in runoff irrigated fields of all types (Smith 2012: Table 8). At Yunge Hills, weedy annual pollen concentrations are roughly 10 percent higher across agricultural contexts compared to Poshu'Owingeh. The ubiquities and richness of other potentially cultivated and encouraged plant families – gourd (*Cucurbita*), mustard (*Brassicaceae*), buckwheat (*Eriogonum*), mallow (*Sphaeralcea*), and purslane (*Plantago*) – suggests that these economic wild taxa might have been more diverse at Yunge Hills compared to Poshu'Owingeh. The order of magnitude difference between Poshu'Owingeh and Yunge Hills cotton concentrations cannot be explained by differential preservation or differences in sampling protocol. At both sites pollen samples are well preserved, with very little mixing of recent pollen into agricultural layers. The relative concentrations of degraded grains (Appendix 3: Figure 4) follow similar trends at Poshu'Owingeh and Yunge Hills, suggesting that the conditions of pollen preservation are similar at both locations. Pollen records at each site are also sensitive to the unique history of population and land use change, reinforcing the conclusion that the pollen records at these two sites accurately reflect vegetation changes.

Conclusions: population history and agricultural change in northern New Mexico

The uneven history of spatial expansion of farming villages and asynchronous population growth in the Tewa Basin reported in Appendix A suggests complex drivers of settlement change. Local demic diffusion, migration, and intraregional relocation due to population pressure on recourses are implicated by a synthesis of the results of each study. It is possible that climate change, agricultural innovation, and the development of new exchange networks led to opportunities for farmers in the Chama Basin in the 14th century that had not existed in the past. This could partially explain the late dispersal of agricultural villages in the region.

Pollen evidence from gravel mulch at Poshu'Owingeh and elsewhere in the Northern Rio Grande suggest that cotton was the primary crop grown in these contexts. Appendix C reports high cotton pollen concentrations in direct association with gravel mulch and suggests that cotton agriculture may have been important as early as the middle 14th Century A.D. in the Chama Basin. Soil evidence detailed in Appendix B indicates that on average, gravel mulch fields receive[d] increased water influx from storm runoff. The exact mechanisms for this are complex and probably vary across the landscape. Based on the phenology of cotton and the amount of water needed to produce the observed changes in leaching intensity in the upper soil profiles, the gravel mulch-cotton complex probably relied heavily on monsoon precipitation to replenish soil moisture lost through transpiration. This supports a hypothesis that cotton played an important role in the rapid socioeconomic growth of the region.

Paleo-proxies for summer precipitation cited in Appendix B show that the climate in the NRG during the 14th century A.D. could have been more suitable for this hypothetical gravel-mulch cotton complex, and the timing of the expansion of agricultural villages through the Rio Chama Basin coincides with optimal conditions. The coincident development and spread of gravel mulch-cotton complex suggests that rapidly changing climatic conditions promoted the development of the cotton-based component of this economy. Many of the large-scale climate changes producing unpredictable changes for societies in the San Juan Basin are probably implicated in the opportunities created in the Chama Basin for runoff irrigated cotton cultivation. The timing of these changes suggests that people responded rapidly to changes in climatic conditions which created opportunities for economic and demographic expansion. In this way, flexible social institutions, flexible settlement patterns, and technological innovation are probably important components of social resiliency for middle-range food producing societies.

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APPENDIX A: RECONSTRUCTING THE SPREAD OF FARMING COMMUNITIES IN THE TEWA BASIN, NORTHERN NEW MEXICO

Introduction

The dispersal of agriculture across the globe was one of the most consequential processes in human history. The spread of agriculture fundamentally changed human evolutionary, cultural, and environmental history, and reconstructing the process has been a focus of archaeology for more than a century (Trigger 2006). Studies suggest that local factors crucial to determining the dynamics of the spread of farming include: (1) sources of population growth (*in situ* or migration), (2) climatic and human caused environmental change, (3) technological change, and (4) interactions between migrants and autochthons. In one well documented case study, anthropogenic environmental change, landscape learning, agricultural innovation, and interaction with autochthons structured the dispersal of farmers through geographic barriers (Grollemund et al. 2015; Klieman 2003; Patin et al. 2017; Russell et al. 2014; Vansina 1995). However, the specific roles of abrupt climate change, the cumulative effects of anthropogenic landscape modification, and long-term cultural interaction and adaptation is a point of uncertainty (Ehret 2015; Garcin et al. 2018).

Different scenarios imply a continuum of processes by which the history of agricultural expansions could unfolded: from a reactive process contingent on climate change opening favorable agricultural niches and favoring rapid demic expansion, to a self-reinforcing process of cultural interaction, learning and innovation, and ecosystem engineering over centuries to millennia resulting cumulative socioeconomic and socioenvironmental change. Detailed case studies of past population expansions and developing complexity in food producing societies could help understand how these factors interact to produce social change.

This paper reconstructs a small-scale agricultural expansion, near the end of the precontact dispersal of domesticated plants and animals in the southwestern U.S. in a richly described archaeological context to examine cultural and environmental contingencies of the process. Analysis of smaller scale case studies can help answer questions about characteristics of expanding populations, environmental factors that affect colonization of uninhabited landscapes, and testing models of historical and evolutionary interest (Romanowska 2015). The small scale of the study decreases analytical complexity because the mean expansion rate is less likely to be influenced by large scale geographic heterogeneity. The rich history of archaeological research in the Southwest allows investigation of the role of climate change, agricultural change and technological innovation, and cultural interaction in shaping the tempo of expansion.

This article addresses the problem by considering the spatial spread of agricultural communities in the Northern Rio Grande (NRG) area, specifically the Tewa Basin after the 10th century A.D. (Figure A.1). The rate and tempo of settlement expansion in the Tewa Basin is reconstructed and this information is used to make inferences about the source population and to assess how the expansion of farming settlements was contingent on the history of population growth inferred from other data.

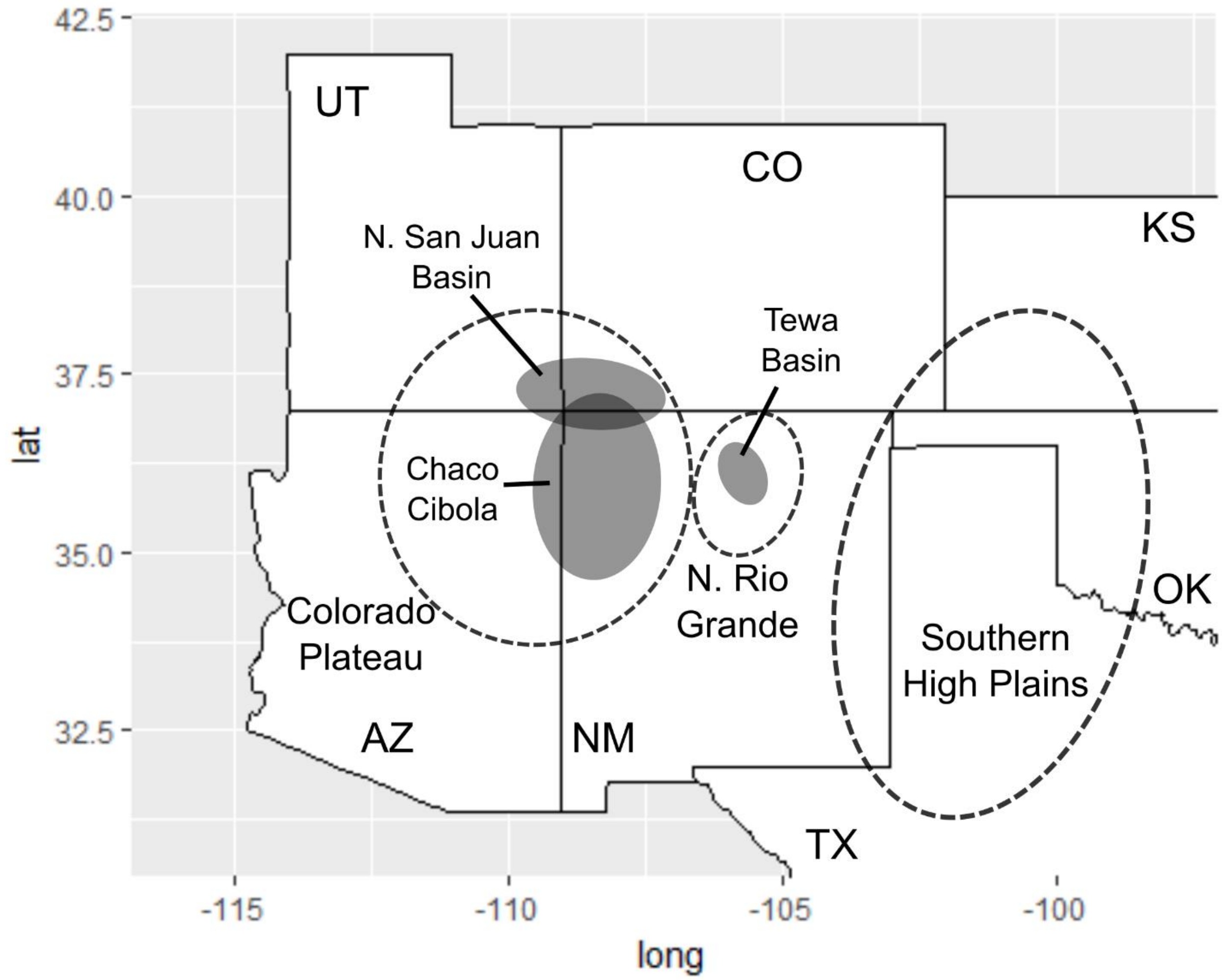

Figure A.1. Location of culture areas and geographic regions mentioned in the text.

Contemporary Tewa speaking communities are located around the Rio Grande River north of Santa Fe, New Mexico. Archaeological evidence for the extent of ancestral Tewa settlements comes from the distribution of Black-on-white painted pottery with distinct pastes – referred to in this study as Tewa Series pottery – and villages ranging from hundreds to thousands of rooms in multistory blocks. The extent of the ancestral Tewa Basin is bounded roughly by Rito Frijoles Canyon on the Pajarito Plateau in the southwest corner, the Rio Tesuque in the southeast, Abiquiu Reservoir on the northwest, and the upper Ojo Caliente drainage on northeast (Figure A.2). (Kohler 2004; Schillaci and Lakatos 2017).

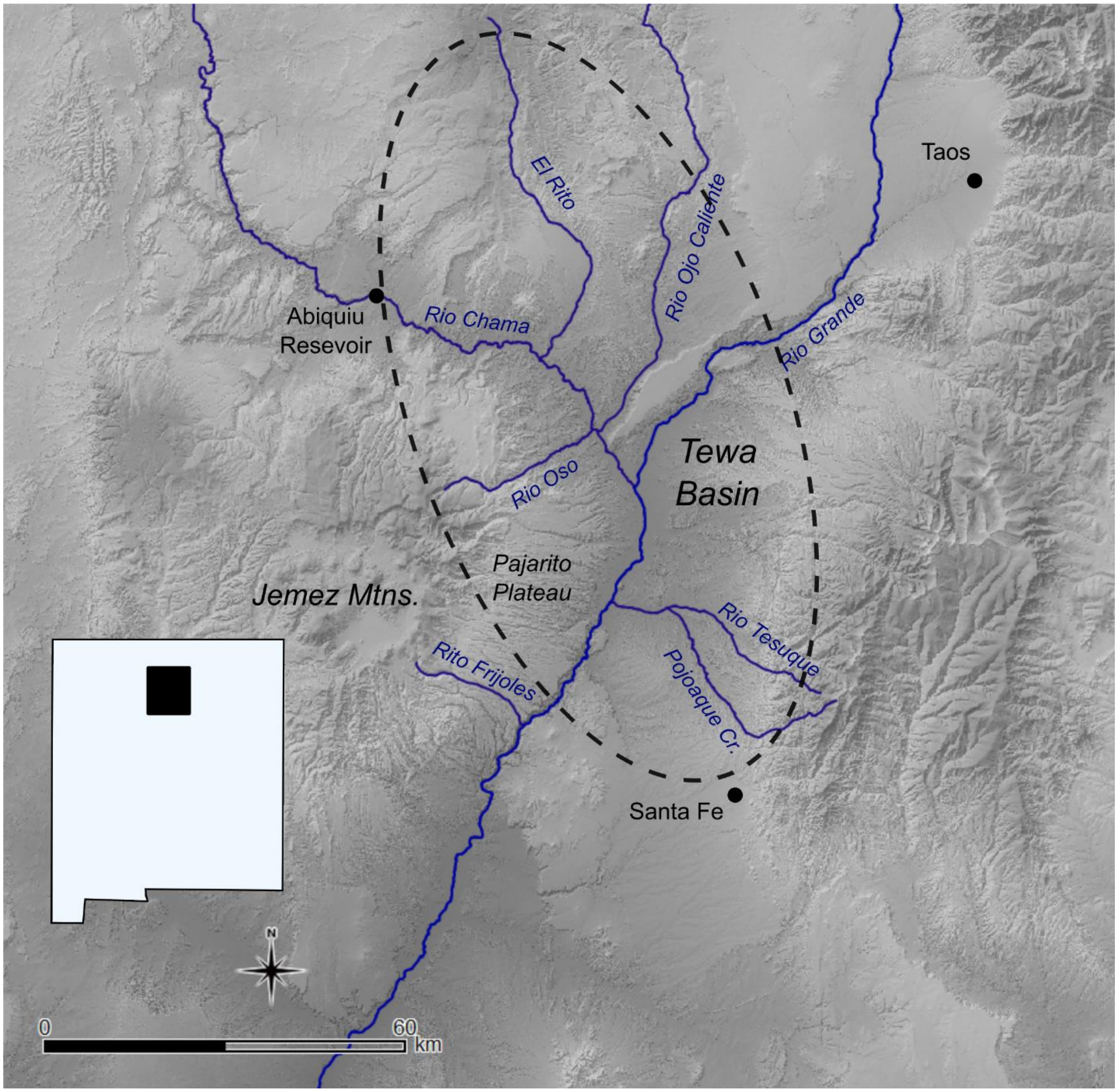

Figure A.2. Overview of the Tewa Basin and physical features mentioned in the text.

The spread of domesticates through the Southwest and the social and demographic changes caused by agriculture began millennia before the appearance of farming villages in the

Tewa Basin. Maize dispersed from Central America through the southern Southwest and arrived on the Colorado Plateau by ca. 2200 B.C. at a rate of ca. 1.3 km yr^{-1} (Merrill et al. 2009), a speed consistent with a mixture of demic and cultural diffusion (Fort 2012; Jerardino 2014). DNA, skeletal age profiles, and archaeological evidence indicate demographic expansion across the Southwest during the last millennium B.C. and first millennium A.D. (Kemp et al. 2010; Kohler and Reese 2014). During this period of demic expansion, maize came to fill new anthropogenic niches across the Colorado Plateau created by the development of a variety of dryland agricultural technologies (Kohler 1993). By the end of this period, maize constituted more than half of the diet of individuals living in agricultural villages on the Colorado Plateau in southern Utah and Colorado (Hard et al. 1996).

In the NRG the oldest maize found in a rock shelter in the southern Jemez mountains dates to between 1190 B.C. to A.D. 50 (Ford 2013). Maize pollen is found in Rio del Oso alluvium in strata post-dating about 1450 B.C. and increases in prevalence by 300 B.C. (Periman 2005). Northwest of the Tewa Basin, in the upper Rio Chama valley, maize has been dated to between A.D. 200 and A.D. 400 (Vierra and Ford 2007). To the south of the Tewa Basin, in the Santa Fe area, pit house communities with below ground storage features are dated to between A.D. 400 and A.D. 600 (Post 2013). Unlike the upper San Juan Basin, maize agriculture in the NRG during the first millennium A.D. is interpreted as being focused on areas of moist soils with high water tables. Maize with morphology described as Puebloan appears in stratigraphic levels dating to the 11^{th} century A.D. (Ford 2013). Abrupt declines in arboreal and grass pollen coupled with increases in disturbance taxa in the Rio del Oso suggest that land clearance increased in the Rio Oso drainage sometime after ca. 1000 A.D. (Periman 2005).

The spread of agricultural villages in the Tewa Basin lagged other culture areas by centuries, and local population increase is attributed to a migration of people from outside the area (Clark et al. 2019; Orcutt 1999; Ortman 2012). Population densities in the Tewa Basin were low until the end of the 13th century when groups began to move into the area after the sociopolitical dissolution in the San Juan Basin and Mesa Verde areas, though exactly how small populations were prior to the end of the 12th century remains an empirical question (Schillaci and Lakatos 2016; 2017). However, by the 15th century, the Chama Basin contained the largest adobe room block villages in the region (Crown et al. 1996; Duwe et al. 2016), and the total population of the Tewa basin may have eclipsed 20,000 individuals (Eiselt 2019; Eiselt et al. 2017; Ortman 2014). Although there are alternative hypotheses involving lower total population figures (Anscuetz 2007), the delayed expansion in the northern Tewa Basin and the abrupt increase in population are indisputable. Therefore, isolating the dynamics of this expansion and comparing it to records of population, social, and environmental change would help advance general understanding of the drivers of population expansion and the spread of agriculture as well as shed light on this archaeological problem.

Methods and material

This study reconstructs the speed of agricultural settlement expansion from a network of archaeological sites across the Tewa Basin. Reconstructed speed is then used to evaluate models of regional population history to infer the source of the population expansion and compare the Tewa Basin expansion to expansions of farming settlements elsewhere. The dataset used in this study is comprised of hundreds of observations that provide a low level of chronological detail. These low-resolution data are combined statistically to predict a continuous surface of age ranks, which are calibrated with selected sites with confident age estimates. The result is an estimate for the time of first arrival of agricultural villages for the Tewa Basin.

Dispersal speeds have provided information on a variety of human population expansions. Previous studies have used reconstructed dispersal rates to estimate parameters for reaction-diffusion models or test demographic hypotheses (Fort 2009; Fort and Pujol 2007; Steele 2009). This approach has also been used to study the spread of late Paleolithic cultures in Europe and North America (Fort et al. 2004; Hamilton and Buchannan 2007; Steele 2010), Neolithic farmers across Europe (Ammerman and Cavalli-Sforza 1984; Gkiasta et al. 2003; Pinhasi et al. 2005), and the settlement of islands across Oceana (Fort 2003). More recently, observed dispersals have been used to test hypotheses and propose new models for population dynamics and agricultural spread across Africa (Jerardino et al. 2014; Russell et al. 2014). This study follows others by calculating the speed of settlement expansion using a regression to predict the age of a site based on its distance from a starting point (Ammerman and Cavalli-Sforza 1984; Fort 2009; Steele 2009). This formulation is the inverse of a rate calculation (distance / time), but distance is the appropriate independent variable because it is more precisely known (see Silva et al. 2014: 7). The speed of settlement expansion is therefore calculated as the inverse of the regression slope, and standard error is proportional to the product of the regression error and the squared inverse of slope (see Demidenko et al. 2013).

Models for the source of population that drove settlement expansion in the Tewa Basin are evaluated with a modified Fisher-Skellam logistic reaction diffusion equation. This model and later modifications serve as the basis for predicting the speed of population expansion given certain demographic and social parameters. Skellam (1951) deduced an application of Fisher's (1937 reaction-diffusion system to model the spatial distributions of biological populations, and this has become the prototype model for spatial population dynamics (Cantrell and Cosner 2003:141). Steele (2009) provides an accessible mathematical overview of the classical Fisher-Skellam model, as well as many archaeological applications. In this system, the velocity of an expanding population (*v*) approaches:

$$2(D\alpha)^{1/2} \tag{1}$$

Where *D* is a dispersal constant which represents the mean dispersal rate for individuals between birth and reproduction (Cantrell and Cosner 2003) and is equal to:

$$\pi\frac{\lambda^2}{2d\tau} \tag{2}$$

Where λ is the distance some individual moves from their birth place in generation time τ, and *d* is the number of dimensions being modeled (in this case 2). Fort (Fort and Mendez 1999; Fort and Pujol 2007) modified the basic Fish-Skellam equation to calculate the time delayed wavefront velocity accounting for a time delay between birth, reproduction, and dispersal which to a first approximation:

$$\approx 0.7v \tag{3}$$

A spatial database of 1,726 archaeological sites was used to determine the rate of population dispersal across the Tewa Basin. All site types were included in the database from isolated finds of artifacts or rock art to the largest villages. However, this study is concerned with the expansion of villages, the locus of primary residence for agricultural populations, defined as sites containing 50 or more rooms (see Eiselt 2019; Ortman 2012 for discussion). Therefore, while the spatial relationships between all sites was informed in the spatial prediction, only sites with 50 or more rooms were included in the velocity regression.

Calculating the rate of dispersal depends on knowing the dates when sites were established. The date which most closely approximates the founding of sites with architectural features was derived from previous syntheses, site reports, and surveys (Adams and Duff 2004; Adler 1996; Beal 1987; Boyer and Lakatos 2000; Duwe 2011; Ellis 1989; Fallon and Wening 1982; Hewett 1906; Hibben and Stallings 1937; Jeançon 1923; Lent et al. 1994; Luebben 1953; Mathien 1990; Mera 1934; Ortman 2012; Peckam 1984; Robinson and Warren 1972; Robinson et al. 1972; Snow 1963; Stubbs and Stallings 1953; Towner 2008; Wendorf 1954; Windes and McKenna 2006; Wiseman 1996;). Site chronologies were estimated using the presence/absence of decorated pottery, mean or composite pottery dates, tree-ring dates, and radiocarbon measurements from published sources.

Most sites have only been tentatively dated to broad time periods (essentially an ordinal measure), and most others lack any age information at all (Table A.1). If unaddressed, this data deficiency would either disqualify most sites from study or dilute true temporal patterns. To solve this problem, missing dates were interpolated using a spatial prediction. Interpolating the spatial trend in the categorical age of sites, calibrated with the most confidently known ages, increases the precision of the velocity calculation by boosting the degrees of freedom of the regression model for expansion rate. Modeled site ages reflect the trend in the "first arrival" date of villages in the region. Plotting the gridded area assigned to each year or decade in the model provides a time series of the rate of population expansion. This provides a means to visualize spatial expansion and compare it to other phenomena such as population growth rate, climate change, and the appearance of new technologies. Because the sample of sites with well replicated founding date estimates is small (n = 17), an area estimate based on this dataset alone would have incomplete spatial coverage and could be severely biased. Sites with an evidence based, though less robust, founding date estimates (n = 405) tend to be assigned to the nearest half century, and these dates are retained in the velocity regression, and because only village size sites are included in the velocity calculation, most sites with interpolated dates are excluded. These steps help prevent a tautological and deterministic analysis by overfitting modelled dates to sites which already have some information on their age. Rather, interpolation is only used for village size sites with no justifiable founding date assignment in the literature (n = 30).

The spatial relationships between the hundreds of smaller sites that tend to be left out when discussing large scale trends in settlement patterns is potentially important, and this modelling effort is an attempt to include such information to reconstruct the trend in overall settlement expansion. Importantly, including many non-architectural, pottery only sites, brings in data on the earliest ceramic period visits to a location. Allowing this information to influence the ordinal ranks of interpolated sites could potentially challenge conventional wisdom on the timing of population expansion in the area by focusing the modelling effort on very earliest arrivals (for example see Schillaci and Lakatos 2017 for a discussion of the implications of dates for the earliest pottery types in the Tewa Series). This analysis attempts to balance the inclusion of a maximum amount of information (via interpolation), wariness of reifying current models (by using only handful of well dated sites), while trying to avoid deterministic outcomes (by overfitting modelled dates). To summarize: (1) sites that lack empirical founding dates are assigned an ordinal age rank based on their spatial relationship to all other ancestral Puebloan sites in the area; (2) this interpolated rank is calibrated based on a smaller number sites with high confidence founding dates; (3) the speed of population expansion is calculated from sites greater than 50 rooms; and (4) interpolated calendar dates are only used for sites greater than 50 rooms and without any justifiable founding date.

The process of interpolating ordinal site age is outlined here. First, all sites were ranked based on the reported earliest pottery type in the Tewa Black-on-white series (Santa Fe B/w, Wiyo B/w, Abiquiu B/w, Bandelier B/w, and Sankawi B/c) and its locally made or imported antecedents (Kiatuthlanna B/w, Red Mesa B/w, and Kwahe'e B/w). The calendar age ranges of Tewa Series pottery production continue to be refined, but the order of the sequence is well known (Habicht-Mauche et al. 1993; Mera 1934; Ortman 2014; Schillaci and Lakatos 2017). After ranking each site based on the earliest type present, the spatial trend of the ranks was identified and cross-validated. Finally, a subset of archaeological sites with independent chronologies was used to calibrate the ordinal age surface and transfer the mean ranks of each grid cell to a calendar age. This approach assumes that (1) the spatial trend in the temporal pattern of ceramic deposition is spatially autocorrelated, and that (2) trends in the ordinal ages of large numbers of sites will covary with their true calendar ages. The first assumption is based on the fact that spatial dependence and autocorrelation are ubiquitous geographic phenomenon, including site and artifact distributions (Kintigh and Ammerman 1982; O'Sullivan and Unwin 2010). The second assumption is an empirical question to be addressed in this study by cross-validation.

Spatial interpolation techniques have proved useful for estimating human population dispersals from archaeological data (Gkiasta et al. 2003; Jerardino et al. 2014; Pinhasi et al. 2005; Russell et al. 2014). This paper used the ordinary Kriging approach for spatial prediction from a point pattern. In ordinary Kriging, spatial data are decomposed to find a two-dimensional deterministic mean structure (Cressie 1988). Kriging was accomplished using the gStat package in the R statistical computing program with supporting packages used to facilitate spatial statistics and GIS functions (Pebesma and Graeler 2019). An algorithm was written in R to automatically perform ordinary kriging on a set of spatial points to iteratively choose variogram models and parameters. Kriging produces a continuous grid of observations from spatial point patterns converted to a discontinuous grid. The point pattern site data were converted to a 2 km grid topology by calculating the mean ceramic rank for all sites in each grid cell. The robustness of the resulting prediction was cross-validated by interpolating two random splits of the point pattern and comparing it to random splits of the calibration data set. Agreement and error coefficients (Pearson's r and root mean squared error (RMSE) respectively) were computed between the two split predicted surfaces and each predicted surface to the calibration split. This procedure was repeated (n = 999) with random splits of the data, and the mean coefficients were evaluated between different interpolation methods and with varying grid resolutions. The maps of each split were also checked for visual consistency through the cross-validation runs.

A total of 17 sites were partitioned as calibration data where the general span of occupation estimated from diagnostic ceramics is replicated by tree-ring dates, or less frequently, radiocarbon age determinations (Table A.2). The calibration dataset represents sites with the best validated calendar age for its establishment. Converting the ordinal age surface to calendar years was accomplished by predicting the age of a calibration site with the interpolated age rank of its grid cell ordinary least-squares regression. Sites adjacent to the Tewa Basin on the south were included in interpolation and calibration but were excluded from the calculation of the dispersal rates. This step created a buffer around the study area to mitigate the loss of neighboring points for the area of interest – e.g. pushing the boundary problem for spatial analysis beyond the study area.

Table A.1. Summary of dataset used in the age interpolation and wavefront speed calculation.

Data type	Size	Data use
Surface finds of painted pottery	408	Age rank used for interpolation; not used in wavefront calculation.
Architectural features with painted pottery recorded but NO calendar age estimations	896	Age rank used in interpolation; modeled age used in wavefront calculation. This includes room blocks, mounds of "melted" adobe, isolated room blocks, and room depressions, cavates, and rock shelters.
Architectural features with painted pottery recorded AND calendar age estimations	405	Age rank used in interpolation, published age used in wavefront calculation.
Architectural features with best replicated calendar ages	17	Calendar age used in model calibration; published age used in wavefront calculation

Table A.2. Table summarizing dates of archaeological sites used to model the interpolated age surface.

Site (LA)	Name	Tree-ring founding date	Ceramic age rank	Published founding age estimate	Founding date used in this study	Notes and Reference
71	Howiri	1412*	5	1377; 1400	1400	Duwe 2011; Fallon and Wening (1982) Beal (1987); Robinson et al. 1972
274	Poshu	1421	6	1375	1375	Jeancon 1923; Robinson and Warren 1971. Cluster of non-cutting tree-ring dates at 1350
297	Ponsipa	1374	5	1300; 1312	1340	1343 is midpoint of Duwe's (2011) estimate and the diffuse cluster of non-cutting dates and is also near the establishment of Duwe's component two. Bugge 1978; 1979
301	Tsiping	1306*	5	1275; 1317	1306	Duwe 2011; Hewett 1953; Robinson 1972 et al. 1972
380	Hupobi	1335*	4	1350; 1363	1350	Mera 1934; Duwe 2011
545	Water Canyon Ruin	1302*	4		1302	Towner 2008; Adams and Duff 2004
632	Pose	1373*	5	1325; 1364	1370	Mera 1934; Duwe 2011
835	Pojoaque Grant Site	1020*	1	600; 910 - 1160	1015	Robinson et al. 1972; Wiseman 1996; Boyer and Lakatos 2000
908	Tsama	1231	4	1250; 1250-1275	1250	Includes both Tsama (LA908) and West Mound (LA909). Ortman (2010); see also Windes and McKenna (2006) and Adams and Duff (2004: Appendix)
920	Riana	1335*	5	1300	1335	Hibben 1937; Robinson et al. 1972
3119			2	965-1140	1020	Boyer and Lakatos 2000 Schillaci and Lakatos (2018) report 14C ages with a midpoint roughly 1020 AD.
3505	Pallisade	1312*	5	1300	1312	Peckam 1984
3852		1085	3		1200	Kohler 2004; Towner 2008
60372	Burnt Mesa pueblo	1250	3	1275	1250	Kohler 2004; Towner 2008
6462	North Bank Site	1128*	3	1100	1128	Lange 1968; Towner 2008
8681	Fulton's 190	1191	4	1150-1250	1200	Towner 2008
12121	Across the Way House	1150*	3	1100	1150	Hubble and Traylor 1982; Towner 2008

* Indicates tree-ring cutting date cluster.

Results

The inclusion of non-architectural surface ceramics significantly improved the robustness of the resulting interpolation. The strength of correlation between cross-validation splits improved by 150 percent when non-architectural sites were included in the interpolation (from r = 0.33 to r = 0.84), while RMSE was virtually unchanged. The correlation between the calibration data set and the ordinal surfaces produced from cross-validation splits was roughly the same when non-architectural sites were included in the data set (r = 0.41). These results suggest that increasing data density improved the robustness of the interpolation to outliers and missing data while having little effect on accuracy. It also indicates that surface pottery reflects the same spatial trend as sites with architectural features. Interpolation by inverse distance weighting produced similar age trends, but only at lower resolution.

The ordinal age surface interpolated from the entire non-calibration dataset is a good predictor of the founding age of the best documented site chronologies ($R^2 = 0.73$) (Figure A.3). The predicted age surface shows a clear trend in the “first arrival” date of grid cells increasing in a roughly radial manner from southeast to northwest (Figure A.4). Examining the predicted first arrival surface shows that the earliest villages in the Tewa Basin are predicted in the lower Tesuque and Pojoaque drainages, whereas the latest villages are predicted for the Abiquiu Dam area and the upper Ojo Caliente valley.

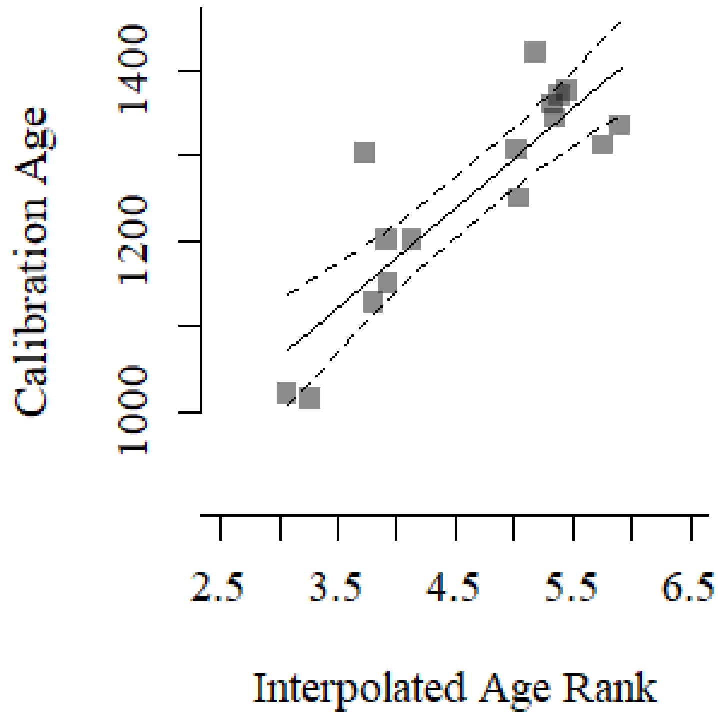

Figure A.3. Fit of the interpolation model. Founding age of sites in the calibration data set (x-axis) predicted by the interpolated ranked age surface (y-axis).

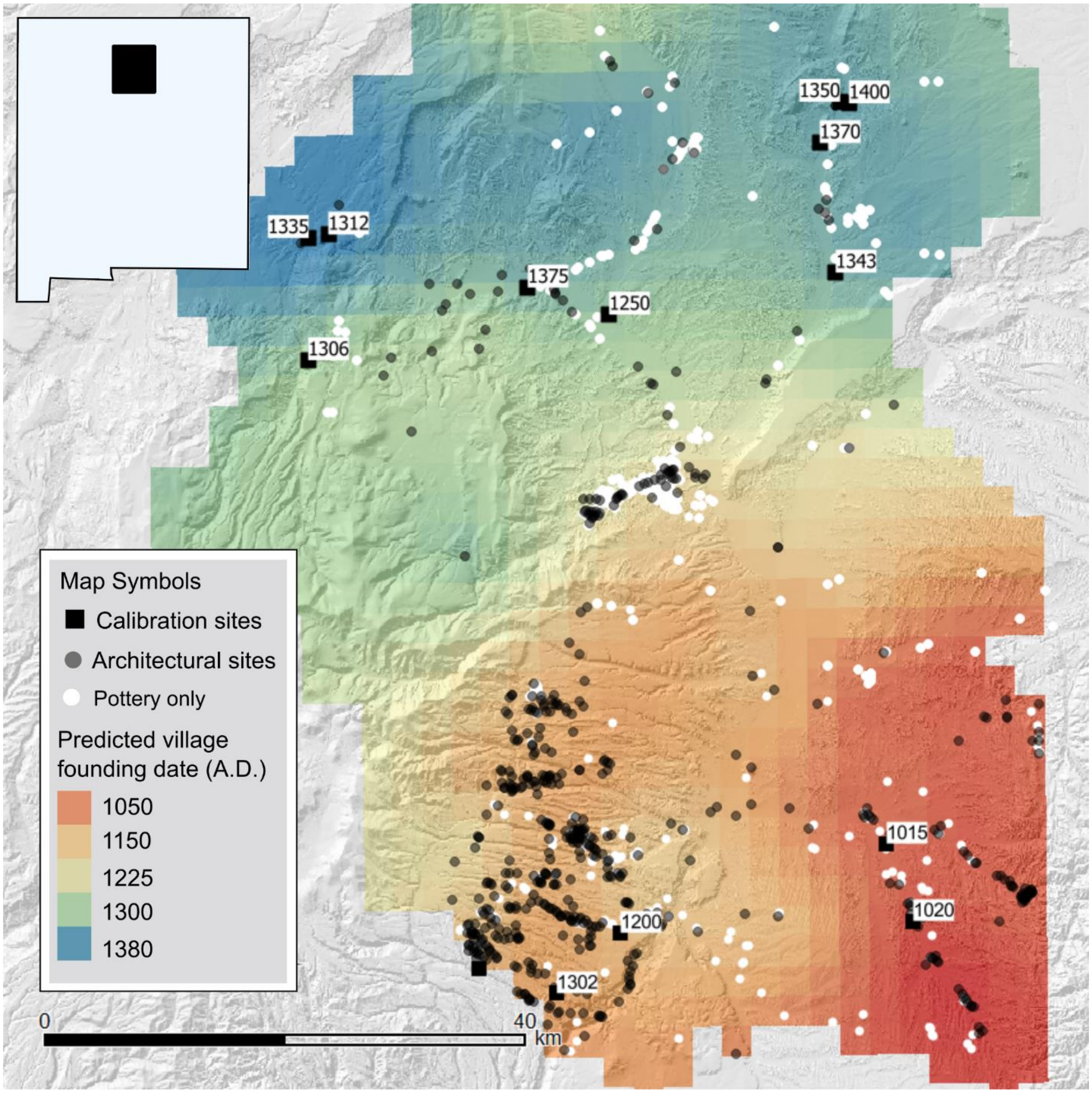

Figure A.4. Predicted age surface for the Tewa Basin (shaded region). Calibration sites (squares) are shown with their estimated founding dates (year A.D.).

Including all sites with any record of architectural features results in an overwhelming noise-to-signal ratio for the calculation of dispersal speed using the regression method. Therefore, only sites with a record of more than two rooms are included in the dispersal rate estimate. From the regression of site age on distance from the oldest grid cell, the reconstructed speed of settlement expansion was between 0.25 and 0.47 km yr^{-1} (95% confidence) (Figure A.4). A similar speed is reconstructed when interpolated ages are excluded, and a simpler calculation using the square root of area divided by elapsed time (Skellam 1951) yields roughly 0.2 km yr^{-1}. The advantage of basing the expansion rate estimate on both published and interpolated ages comes from the improvement of the precision of the regression slope enabling exploration of dispersal distances and inferences on the source of people contributing to the population expansion.

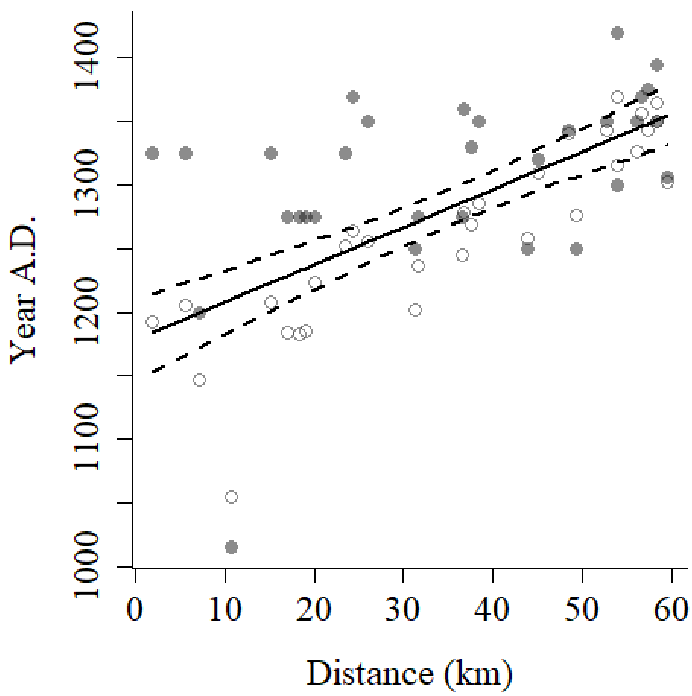

Figure A.5. Regression model for the speed of settlement expansion across the Tewa Basin calculated from sites with calendar ages and those with ages predicted from the interpolation of age ranks. Closed circles are data sites with published age estimates and open circles are ages predicted from the interpolated first arrival surface.

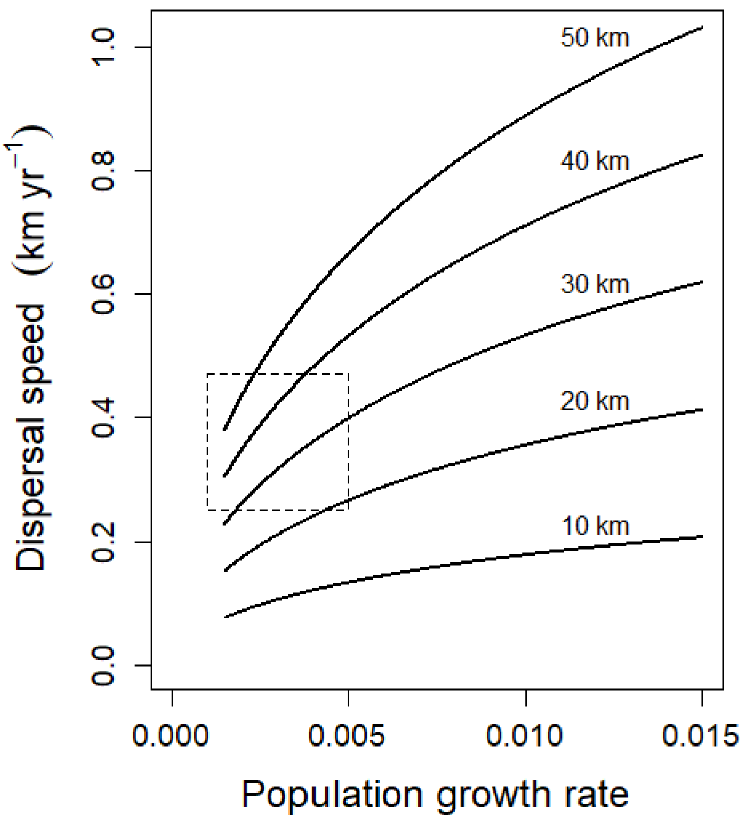

Figure A.6. Average rate of population expansion (y-axis) as a function of growth rate (x-axis) and generational dispersal distance (solid lines). Dashed box indicates the bounds of a population history based on the expansion speed reconstrcuted in this study and realistic population growth rates.

Average dispersal distances (km/generation) for communities moving into the Tewa Basin can be reconstructed from the observed dispersal speed and population growth rate in a time delayed reaction diffusion equation (Equation 3). Genetic studies of ancient agricultural populations reconstruct maximum growth rates of around 0.1-0.5 percent (Gignoux et al. 2011). This figure is consistent with long term growth rates of pre-industrial agricultural societies (Cowgill 1975), as well as growth rates recently inferred for the precontact southwestern U.S. (Phillips et al. 2018). On the basis of ethnographic data, Fort (2012) utilized a general dispersal kernel with a range of values from 2 to 100 km and a weighted mean of 14 km per generation. The work of Aubán et al. (2015) demonstrates that a fat right-tailed dispersal kernel may be more realistic in long distance “leap-frog” dispersal with occasional dispersals of 25 km to 100 km and a mean around 40 km (see also Bogucki 2003). Long distance migration has been proposed to explain the peopling of the Tewa Basin for years (Reed 1949), and this is considered by many the most likely dispersal process (Ortman 2012; Clark et al. 2019). With generation length of 25 years and realistic growth rates, the observed rate of expansion in the Tewa Basin is consistent with average generational dispersal distances from 30 to 50 km fully consistent with a leap-frog long distance dispersal (Figure A.5).

The rate of change in the area occupied by agricultural villages (see Figure A.3) peaks several times: at A.D. 1090, 1160, 1285, 1340 (Figure A.7). The earliest peak in spatial expansion occurs just prior to the time that population growth increases to levels suggestive of migration. Growth above the maximum intrinsic rate begins in the 12th century and is accompanied by another peak in spatial expansion at around A.D. 1160. Population growth peaks around A.D. 1280 as a result of migration from Mesa Verde, and this is soon followed by peak rates in spatial expansion. This final phase of settlement expansion corresponds to migration into the Rio Chama basin from elsewhere in the Tewa Basin, most likely from the Pajarito Plateau which experienced earlier population growth resulting in high population densities (Kohler 2004). The period of most rapid spatial spread, with peak rates around A.D. 1340, occurs after regional population growth declines to levels consistent with intrinsic growth suggesting a lag between population growth and spatial expansion.

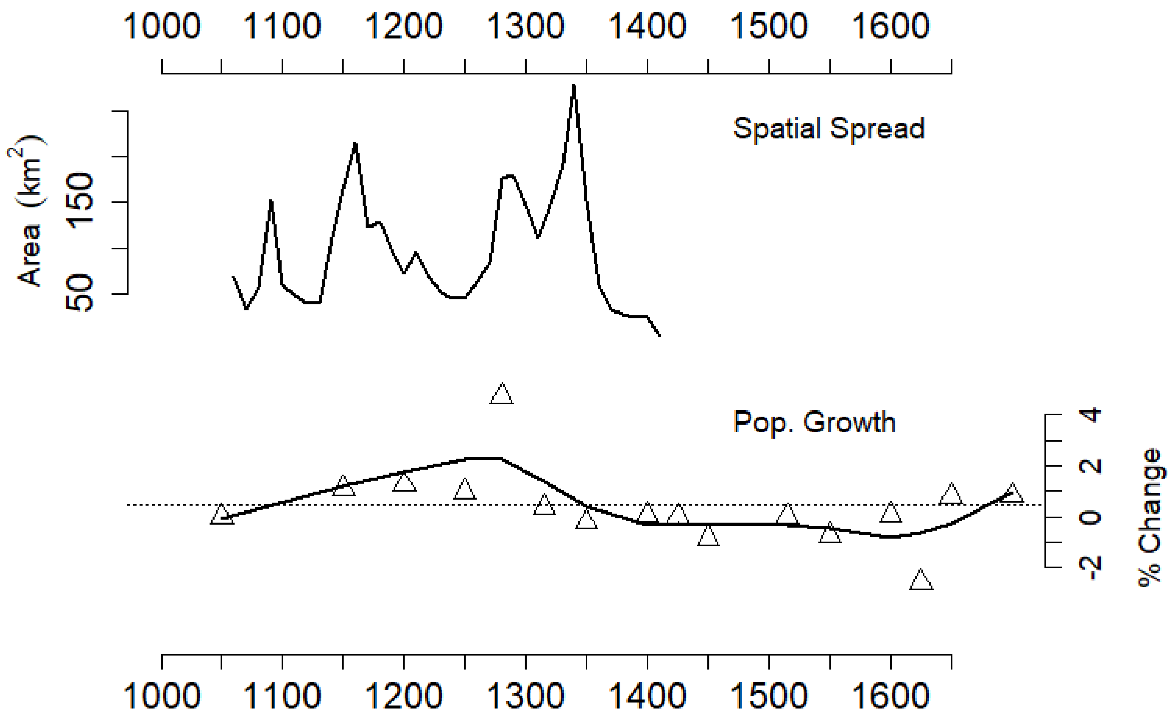

Figure A.7. Population expansion during the 13th and 14th centuries in the Tewa Basin (top) peaks after the maximum rate of population growth reconstructed between A.D. 1250 and A.D. 1280 (bottom). Data points in the growth rate represent the annualized percent change in room counts for the Chama Basin reconstructed by Ortman (2014) (closed triangles). The trend line in population growth is the local regression fit (α = 0.5), and the horizonal dotted line illustrates the maximum intrinsic growth rate discussed in the text (0.5% annually).

Discussion and conclusions

Sites in the Pojoaque drainage are more than 100 years older than predicted by their location and this suggests a discontinuity in the main settlement trend that produced the Classic period Tewa settlement expansion across the Pajarito Plateau and Chama Basin. The cluster of sites near the Pojoaque Land Grant (LA 388, 391, 835, and 3119), are the oldest documented villages in the study area (Boyer and Lakatos 2000; Wiseman 1996). Based on diagnostic ceramics and radiocarbon dates, their earliest architectural levels may date to the late 10th century and were almost certainly occupied by the first decades of the 11th century (Boyer and Lakatos

2000; Schillaci and Lakatos 2017). Early decorated pottery at these sites are mineral painted Black-on-white types (Red Mesa) from outside the NRG and paste and temper changes indicate to some that new arrivals were familiarizing themselves with local resources (Post 2013: 87). Based on the location of the earliest villages in the Tewa Basin and the direction of population movement (Figure A.3), the first migrants may have sought out existing population concentrations beginning in the middle 12th century in the Santa Fe area and the southern edge of the Pajarito Plateau.

Based on the spatiotemporal distribution of residential sites in the Tewa Basin, expansion of farming villages proceeded generally south to north and was relatively slow. The reconstructed expansion rate of 0.3-0.5 km yr^{-1} combined with realistic population growth rates implies a dispersal distance consistent with occasional long-distance movements (up to ca. 100 km) characteristic of a leap-frog dispersal. The estimated long-term average dispersal distance is roughly 30-50 km per generation. If the source of Tewa Basin farming populations was entirely intrinsic (e.g. expansion began in the early A.D. 1000s) the area settled by farming villages should have reached the upper Ojo Caliente by ca. 1100 AD. The growth rate chosen for this analysis (0.001-0.005 annual increase) is indicative of regional population change (Hill et al. 2010; Phillips et al. 2018), which effectively increases the area behind the expanding wavefront to include both sources of population (for example Mesa Verde) and the areas of population gain (the NRG). Only by including distant sources of population can the observed rate of farming expansion be reconciled to realistic population parameters. More important than the specific reconstructed figures for dispersal rate, is that this scenario could be falsified by the discovery of 12th century villages in the Chama Basin. This would increase the reconstructed expansion rate such that intrinsic growth and diffusion could account for the observed spread of villages through the Tewa Basin.

The uneven history of spatial expansion of farming villages and asynchronous population growth in the Tewa Basin suggests complex drivers of settlement change. First, local expansion from intrinsic growth cannot be ruled out prior to the12th century A.D. Because there is no evidence for an early dispersal into the northern Tewa Basin, the first phase of population expansion may have been characterized by gradual diffusion. By the middle 12th century population growth rates are indicative of contributions from outside sources. This could indicate that migration from western population centers began by this time, and synchronous spatial spread could be a product of the settlement of new communities on the margins of occupied areas, analogous to the pattern of population expansion by disjunct migration (Bohannan 1954; Stone 1997). Rapid growth by large scale migration beginning in the middle and late 13th century may have increased population pressure on resources in the southern Tewa Basin and driven expansion into the northern portion of the Tewa Basin. The abrupt increase in the area settled by agricultural villages in the Chama Basin lags population change and suggests complex processes driving growth.

It is possible that climate change, agricultural innovation, and the development of new exchange networks led to opportunities for farmers in the Chama Basin in the 14th century that had not existed in the past. Specifically, favorable climatic changes involving increased summer precipitation may have created a favorable environment for farming with irrigation water from storm runoff (Appendix B). Runoff irrigation infrastructure is documented at several large villages that were founded in the middle and late 14th century in the Rio Chama and Ojo Caliente Valleys. The success of this strategy may have led to greater or more prominent participation in regional exchange systems and encouraged intraregional migration during the early 15th century. Such a pattern of growth is documented at most large villages in the Chama Basin (Duwe 2011), and this process could be involved in subsequent socioeconomic expansion hypothesized to have resulted from increases in population size and connectivity in the Tewa Basin beginning in the 15th century (Ortman and Coffey 2019).

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APPENDIX B: DOCUMENTING THE IRRIGATION FUNCTION AND SOIL QUALITY OF ANCESTRAL PUEBLOAN GRAVEL MULCH FIELDS (A.D. 1350-1550) IN NORTHERN NEW MEXICO

Introduction

Establishing the link between technology, ancient agricultural change, and social resilience is of fundamental importance for understanding long term histories of social development. Detailed case studies show that complex societies were able to adapt to rapidly changing climatic and ecological conditions to a surprising extent (Middleton 2018; Petrie et al. 2017). Technology and innovation play an important role in cultural adaption and socioeconomic change, and feedbacks between resource availability and cultural niche construction adds a level of complexity to models for the development of social complexity. Agricultural technology necessarily alters ecosystem resource flows (e.g. it is a component of niche constructing behavior) and so structures the adaptive environment (Laland et al. 2001). The complexity of ecosystem engineering technology and feedbacks on carrying capacity and population dynamics are key problems for understanding the major divergence in increasing cultural complexity with food production (Collard et la. 2013; Fogarty and Creazan 2017).

Studies of ancient dryland agricultural technology tend to focus on irrigation or water conservation, but despite decades of research there are almost no direct measurements of enhanced subsurface water flux associated with direct precipitation and runoff irrigated agricultural features. This is because environmental changes directly resulting from cultivation or infrastructural intensification are difficult to observe. Therefore, *cultivation legacies* – environmental variables altered by biophysical changes caused by agriculture in the past – are sought instead (Van West 2008). This is based on the observation that cultivation results in the alteration of soil properties that affect soil quality or resilience, or the ability of soils to resist threshold shifts (Cramer et al. 2008). Information on agricultural soils is particularly relevant because inherited and humanly altered soil properties influence the trajectories of agricultural intensification (Richter 2007; Vitousek et al. 2004). Most agricultural soil studies infer changes in hydrologic properties from changes in soil texture, vegetation patterns, soil organic matter (SOM), and SOM linked nutrient cycling. However, this information contributes little to understanding the mechanics of these technologies or their resilience and vulnerabilities to climate change in the past; the timing and magnitude of water flux linked to specific technologies and climate conditions is unknown. This knowledge gap is particularly relevant in regions such as the southwestern U.S. where researchers have traditionally viewed the history of land use in the region as a series of fragile intensification projects driven by demographic growth after the introduction of domesticates and population aggregation (Cordell and Plog 1979).

In the southwestern U.S. a variety of rock based agricultural infrastructure has been traditionally used to reclaim marginal land for cultivation, a process that necessarily involves the modification of natural soil and ecosystem properties (Sandor 2006). This article focuses on sand and gravel mulch fields, an indigenous agricultural technology primarily found in the Rio Chama Basin of northern New Mexico (Figure B.1). Gravel mulch consists of an intentionally placed layer, generally about 10 cm thick, of sand and gravel over the natural A horizon. Data from agricultural experiments suggest that this layer functioned to conserve soil moisture, prevent erosion, and moderate temperature fluctuation. Gravel mulch is unsorted, although large cobbles were removed from gravel mulch to form rectilinear field borders and internal partitions. Fields can range in size from < 10 m^2 to more than 100 m^2.

Evidence for cotton agriculture in gravel mulch fields raises the question as to how these fields functioned. Cotton requires water in excess of the natural precipitation of the region in most years, and the dry fore-summer characteristic of the region's climate could have posed a problem for developing cotton plants (Wrona et al. 1999). Geoarchaeological evidence demonstrates that some fields were connected to a network of ditches and rock alignments that served as runoff irrigation infrastructure (Camilli and Banet 2012). This is best documented in feature excavations from late precontact contexts in the Rio Grande Valley which had most intensive use beginning in the last half of the 16th century A.D. (Camilli et al. 2019). However, gravel mulch is widespread in earlier contexts in the Chama Basin, and was certainly in use in this area before A.D. 1400 and possibly as early as A.D. 1275 (Anschuetz 1998; Moore 2009).

Knowledge on the origins, development, and function of gravel mulch is valuable to models of social change in the region. One hypothesis is that gravel mulch was one component of an extensive agricultural system which both spread environmental risk and produced diverse agricultural goods for intraregional exchange in a ritually mediated system for resource redistribution (Ford 1972). More recent research proposes that gravel mulch was a primary feature of specialized cotton agriculture in parts of the Norther Rio Grande (NRG) region (Camilli et al. 2019). This supports a model for local specialization, the expansion of regional interaction, and increases in social complexity and socioeconomic growth during the late precontact period (A.D. 1450-1540) (Ortman and Coffey 2019; Ortman and Davis 2019). While gravel mulch was undeniably widespread in the Chama Basin (Eiselt et al. 2017), the proposal that gravel mulch supported intensive cotton cultivation through runoff irrigation remains untested.

This study contributes detailed evidence for the effects of irrigation features on subsurface water flux and change in soil quality. I combine typical measures of soil quality in relict agricultural fields with base cation measurements of pedogenic threshold shifts to evaluate both the irrigation function of gravel mulch and address questions about its effect on soil quality. The specific goals of this study are to (1) describe physical and chemical soil properties associated with gravel mulch and link these to changes associated with cultivation, and (2) examine reactive soils constituents to quantify the extent to which gravel mulch alters subsurface water flux.

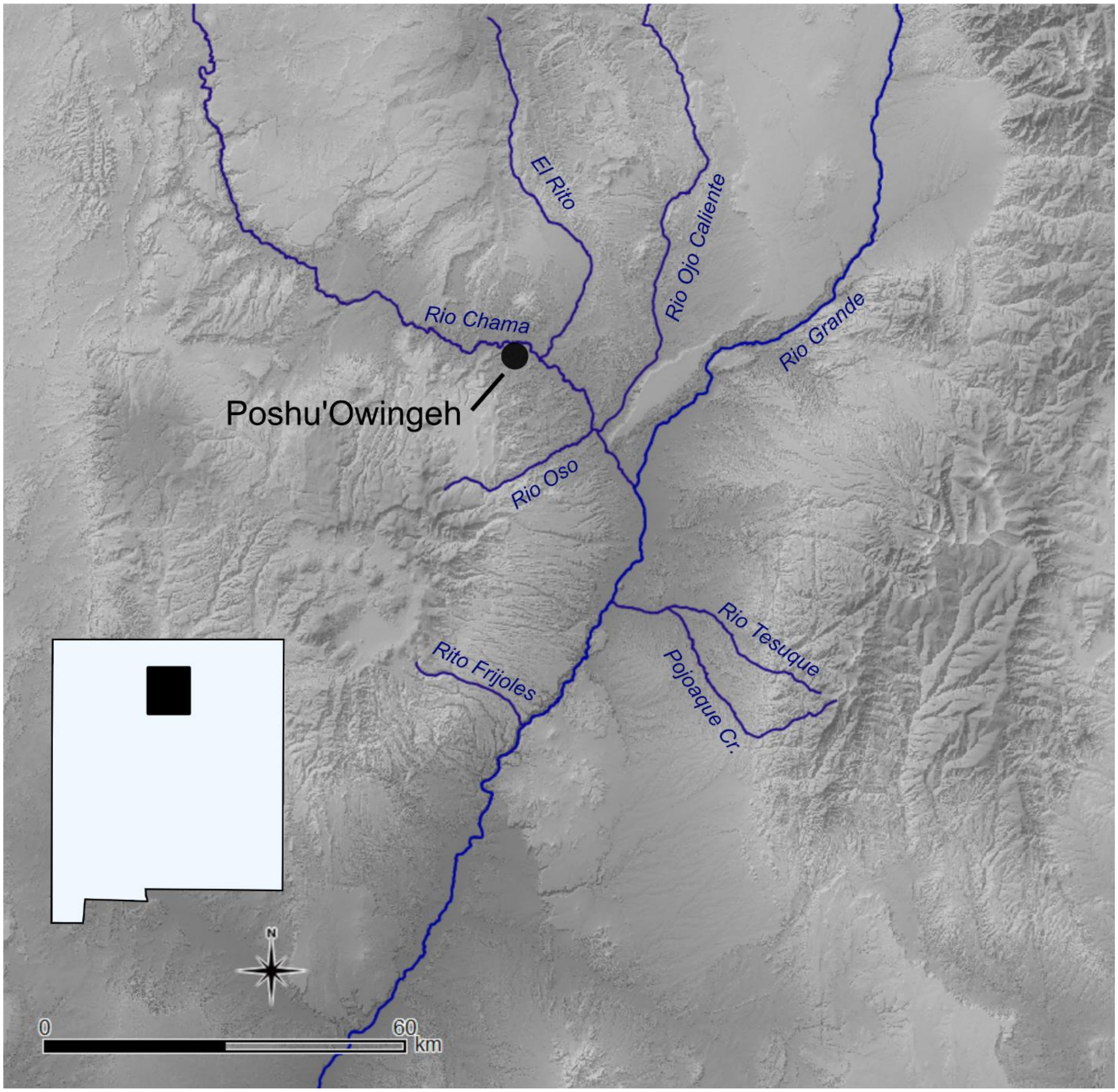

Figure B.1. Overview of the Northern Rio Grande area and the location of Poshu'Owingeh.

This study measures physical soil attributes, water mediated soil reaction products, and indicators of soil quality and fertility in gravel mulch fields around the Ancestral Puebloan village of Poshu'Owingeh (LA 274) (Figure B.2). The purpose was to explore how these fields functioned and to assess long-term soil quality decline. These data are used to build a conceptual model of the function of gravel mulch in the Chama Basin. Such information is important because it is an empirical basis for reconstructing the origins and development of this technology and understanding its resilience and climate vulnerabilities.

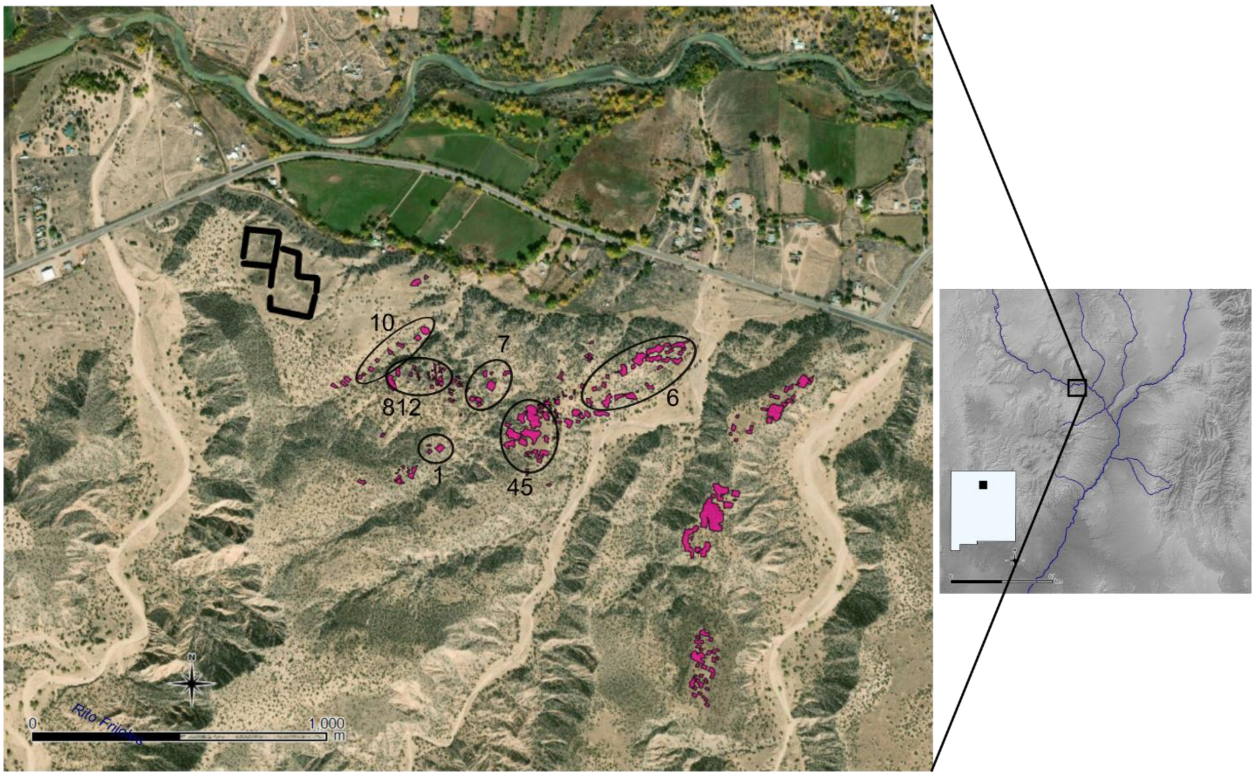

Figure B.2. Location of gravel mulched fields (pink polygons) recorded in this study southeast of Poshu'Owingeh, New Mexico. Thick black lines illustrate the footprint of the room block village at Poshu'Owingeh.

Rainwater run-off harvesting is a low-cost method for increasing agricultural production in drylands, and infrastructure for catching and controlling run-off has been utilized worldwide for millennia (Bruins et al. 1986). Traditional precontact agriculture in the Southwest involved extensive use of rock-based run-off irrigation facilities in every inhabited biome - from the arid desert basins to cool semi-arid pinyon-juniper forests (Berlin et al. 1977; Fish and Fish 1984; Fish et al. 1985; Fish and Nabhan 1991; Ford and Swentzell 2015; Hack 1942; Kruse 2007; Maxwell and Anschuetz 1992; Neely 2001; Spores 1969; Stewart and Donnelly 1943; Sullivan 2000; Vivian 1984; Woolsey 1986). Common field types include check dams across channels, hillslope rock alignments, terraces, rock piles, grids, and sand and gravel mulch. Evidence suggests that in the deserts, rock piles, grids, and alignments supported cultivation of agave, including domesticated forms (Fish et al. 1985; Hodgson and Salywon 2013; Homburg and Lightfoot 2004). In northeastern Arizona and western New Mexico, analogs with contemporary Hopi and Zuni agriculture link ancient run-off irrigation systems on the Colorado Plateau to the cultivation of maize (Homburg et al. 2014; Muencrath et al. 2017). In the Rio Grande Valley, rock alignments, grids, and mulched fields are associated with pollen evidence for both cotton and maize cultivation (Camilli et al. 2019; Dean 1995; Smith 2012). Experiments confirm that gravel mulch benefited crop growth, but treat these fields as isolated features, manually irrigating plants rather than relying on runoff sources and direct precipitation (White et al. 1997). Recent geoarchaeological and paleobotanical fieldwork demonstrate that gravel mulch fields often occur as complexes of mulched plots, rock alignments, and ditches that provide runoff directly to fields (Camilli and Banet 2012; see also Camilli et al. 2019).

Cultivation legacies have been described in a few case studies from the Southwest, but evidence for widespread degradation resulting from precontact land use is not widespread. Given the agricultural diversity of the Southwest, only a small sample of infrastructure types has been studied in detail, and the available dataset is far from complete. Documented cultivation legacies directly associated with run-off irrigation infrastructure in central Arizona include changes in plant biodiversity (Fish 1985; Hodgson and Salywon 2013) and changes in particle size distribution, that affect the ecohydrology of sites, and nutrient concentrations (Hall et al. 2013; Nakase et al. 2014). Some studies have concluded that precontact agricultural features are associated with long-term soil degradation. In western New Mexico, erosion and soil nutrient depletion are recorded in association with check dams and hillslope rock alignments (Sandor et al. 1986). In the Northern Rio Grande, Lightfoot (1990; 1994; Lightfoot and Eddy 1995) proposed that the use of gravel mulch degraded the capacity for soil to replenish nutrients by blocking organic matter deposition. Studies on fields currently cultivated by traditional methods on the Colorado Plateau suggests that run-off irrigation conserved organic matter and soil nutrients and was a sustainable practice (Homburg et al. 2005; Norton et al. 2003; Norton et al. 2007). Overall, evidence for soil degradation resulting from cultivation appears to be rare in the archaeological and geological record in the Southwest (Minnis 2000; Homburg and Sandor 2011, and questions remain about the influence of precontact landscape modification and contemporary ecosystem structure and function (Fish 2000; Briggs et al. 2006).

There is broad agreement that gravel mulch should be associated with some form of cultivation legacy, however there are few actual measurements of this effect. These fields functioned to increase soil water content; agricultural experiments in field laboratories confirmed that lithic mulch enhances crop yields by (1) increasing infiltration of precipitation, (2) conserving soil moisture, (3) regulating soil temperature, and (4) mitigating soil erosion (Adams 1965; Adams 1966; Bu et al. 2013; Fairbourn 1973; Lamb and Chapman 1943; Li 2003; White et al. 1997; Yuan et al. 2009;). Hydrologic simulations using precontact mulched fields as model systems suggest that these fields functioned in much the same way (Dominguez 2000: 216). This study contributes detailed evidence for the effects of irrigation features on infiltration and subsurface water flux and change in soil quality. I combine typical measures of soil quality in relict agricultural fields with base cation measurements of pedogenic threshold shifts to evaluate both the irrigation function of gravel mulch and address questions about its effect on soil productivity. The specific goals of this study are to (1) describe the surface subsoil horizons associated with gravel mulch to link physical soil change to functional soil properties, (2) evaluate measures of soil quality to infer the sustainability of the practice, and (2) examine reactive soils constituents to quantify the extent to which these irrigation features alter subsurface water flux.

The movement of water through the soil profile produces a range of soil reactions which determine pedogenesis at multiple time scales. Agriculture and the construction of irrigation features can alter numerous soil properties that directly affect or indicate a change in water balance, including: texture (causative), A horizon thickness (indicative), organic matter content (causative and indicative), and the down profile movement of soil base ions (indicative). Texture is an inherited soil property and is slow to change in the field, but geoarchaeological investigations in soils altered by precontact and contemporary traditional agriculture show that water and soil management facilities are associated with increased fine fractions that affect soil hydrology (Goodman-Elgar 2008; Hall et al. 2013). For gravel mulch, it is expected that concentrated coarse fraction at the surface will enhance water infiltration beneath mulched profiles. The depth of secondary carbonate accumulation may also be sensitive to long-term changes in water balance because during pedogenesis, calcium carbonate is deposited in the subsoil by leaching processes and reprecipitation that are sensitive to changes in surface permeability (McFadden and Tinsley 1985). When other factors are controlled, the depth of carbonate accumulation is correlated with unsaturated zone wetting depth and ultimately average precipitation (Arkley 1963; Birkeland 1999). Soil organic matter (SOM) is an indicator of both soil quality and net productivity hypothesized to respond to anthropogenic changes in water availability. SOM consists of carbon-based living and dead biomass, as well as the organic compounds of metabolized substances, and reflects the net balance of biomass deposition and microbial respiration (Schmidt et al. 2011). SOM stabilizes soil aggregates and enhances soil porosity and water holding capacity (Dexter 2004), and water availability has positive feedbacks for SOM accumulation via controls on plant productivity and microbial growth (Wu et al. 2011; Moyano et al. 2013). Hypothetically, gravel mulch should have an outsized effect on the surface soil horizons, which is the critical zone of water mediated biochemical soil reactions (Chorover et al. 2007). Water flux determines the differential depletion of soluble base ions (Chadwick and Chorover 2001; Chadwick et al. 2003), and if gravel mulch indeed increases infiltration and water flux, changes in the ratios of calcium (Ca^{2+}) (relatively resistant to leaching) and sodium (Na^{+})(readily soluble) might be observed. Importantly the depth of increased Na leaching under gravel mulch could provide an indication of the extent to which gravel mulch irrigation enhanced water flux.

Soil quality refers to a complex of properties that affect biogeochemical function and agricultural productivity of soils. Usually, quality is measured as soil functional change relative to reference conditions (Pierce and Larson 1993). Physical alterations to soil properties and soil forming conditions produce a cascade of effects on resource fluxes, trophic interactions (microbial – plant – herbivore), and biodiversity (Kardol and Wardle 2010). Worldwide, studies of successional processes and soil properties on old agricultural fields have been a primary source of information for disentangling natural and anthropogenic influences on ecosystems, and cultivation legacies have been observed in worldwide case studies (Fisher et al. 2003; Foster et al. 2003; Vanwalleghern 2004; Dambrine et al. 2007; Monger et al. 2015). Relevant measures of soil quality commonly used in studies of agricultural infrastructure in the Southwest include texture, soil organic matter (SOM) and organic carbon, nutrient levels, A horizon thickness, pH, and bulk density (Homburg and Sandor 2011). In addition to soil properties mentioned in the preceding paragraph, this study measures A horizon thickness, calculates exchangeable sodium percentage (ESP), and measures concentrations of essential plant nutrients nitrogen (N), phosphorus (P), and exchangeable potassium (K^+). These measures evaluate the extent to which gravel mulch may have interfered with organic matter cycling, contributed to soil loss or build up, or influenced soil sodicity, all of which could be potential issues inhibiting the sustainability of this agricultural practice.

Water contains dissolved ions that can build up in irrigated soils over time (Pearson 1960). While calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) are plant nutrients, sodium (Na^+) is not, and is associated with salt toxicity in large quantities (Brady and Weil 2001). In soils, excessive salt can be problematic because it displaces other nutrients at negatively charged exchange sites, and harms the agricultural quality of soils, specifically by soil swelling and dispersion (Sumner 1993). In some cases, runoff irrigation is associated with increased Na^+ levels near the soil surface as dissolved salts are concentrated where water is lost through evaporation (Chhabra 1996). Exchangeable sodium percentage (ESP) is the percentage of exchangeable sodium in the total amount of base ion count and is a common measure of sodicity in agricultural soils (Cook and Muller 1997; Pearson 1960) and is used to assess the sodicity of gravel mulched cultivated soils.

N and P, and K are the most important growth limiting plant nutrients in soil, and these nutrients are linked to the turnover of SOM constituents in soil (Paul 1984). In natural ecosystems, N and P leaching is negligible and SOM deposition balances plant uptake, but under intensive cultivation nutrients can be depleted over years by biomass removal during harvest and physical removal by soil erosion (Frossard et al. 2000). In contrast, K can be leached readily, particularly in acid soils, and is taken up in large quantities by plants (Brady and Weil 2001). Plant available phosphorus (P_{av}) is only a small fraction of the total phosphorus pool in soils, but it is among the most important to plant nutrient status (Brady and Weil 2001). Total phosphorus is perhaps the best quantitative measure of anthropogenic phosphorus in studies comparing cultural (specifically domestic, midden, and intensively cultivated) to natural contexts. In a handful of geoarchaeological datasets, however, P_{av} in dryland soils has been shown to correlate with total P (Holliday and Gartner 2007).

Method and materials

Study site

The field complex selected for study is located in immediate vicinity of the major village of Poshu'Owingeh, inhabited from roughly A.D. 1350 to A.D. 1550 (Fowles 2004; Robinson and Warren 1971; Ramenosfsky and Feathers 2002). The fields were originally cultivated by ancestors of Tewa speaking people currently living in several Pueblo communities around Santa Fe, New Mexico. Pollen evidence suggests that cotton was the main cultivar in gravel mulched fields in the area, but maize and squash pollen taxa are also recovered (Appendix C; Camilli et al. 2019). The field area is at an elevation from 1835 m to 1870 m amsl. Climate is classified as cold, semi-arid steppe (Peel et al. 2007). The climate lacks a true dry season, although roughly half of the average annual precipitation of 276 mm occurs during the summer (Table B.1). Mean annual temperature is 11°C, with the warmest summer month (July) averaging 23°C and the coldest month (January) averaging 0°C. Growing season (May-Sept) averages 19.1 °C while the average minimum temperature shifts above freeze in April and exceed 5°C in May suggesting that crops may have been planted in latest April through May to avoid early season frost. For cotton, requiring a minimum of 80-100 days prior to harvesting mature (if not completely open) bolls, this places harvest no earlier than the first week of July, although August seems more likely based on the timing of the monsoon which begins in the middle of June and would provide important soil moisture during plant development.

Table B.1. Mean climate parameters of the study area prior to recent abrupt warming (1895-1980)[1]

Mean Precipitation	*cm*
Annual	275.6
Oct-Mar	11.4
Apr-May	4.5
Jun-Sept	14.0
24-hour precipitation (1 yr recurrence interval)[2]	2.5
24-hour precipitation (100 yr recurrence interval)[2]	6.6
Mean Temperature	*°C*
Annual	10.7
Growing season (May-Sept)	19.1
Minimum Temperatures	*°C*
March	-3.1
April	1.0
May	5.5

[1]Prism Climate Data Group 2019
[2]Data from Perica et al. 2014

Poshu'Owingeh is situated on the second terrace in the Rio Chama valley. The local topography of the study area is defined by this surface, which is constructed from Pleistocene alluvium characterized by interbedded sand and gravel. The elevation of the Rio Chama near Poshu'Owingeh is 1,800 m amsl and the first terrace surface is approximately 1805 m amsl. A 30-35 m riser separates the second terrace from the first. The upland is demarcated by a rocky scarp of eroded rhyolite, with a footslope elevation between 1865 m and 1870 m amsl. The micro topography on which agricultural features are located consists of a series of low ridges cut by the erosion of the second terrace surface by ephemeral tributaries of the Rio Chama. Erosion has exposed sections of Pleistocene alluvium up to 20 m thick throughout the study area. Sand exposed in the lower 3 meters of the thickest sections is cemented and is overlain by alternating layers of poorly sorted gravel and sand.

The contemporary vegetation community of the former agroecosystem surrounding Poshu'Owingeh is characteristic of the juniper savanna type Southern Rocky Mountain pinyon-juniper ecosystem (*Pinus edulis* and *Juniperus monosperma*) (see Jacobs 2008). Grass (*Poaceae*) represents ≈ 40% of the ground cover across the area. Galleta (*Hilaria jamesii*) is most common with buffalo grass (*Bouteloua dactyloides*) and blue gramma (*B. gracillis*) thriving on gravel mulch. Dropseed (*Sporobolus spp.*), three-awn (*Aristida spp.*), and little bluestem (*Schizachyrium scoparium*) were also observed during field work. One-seed juniper (*J. monosperma*) comprises approximately 30 percent of ground cover with occasional Colorado pinyon (*P. edulis*). Nearly all pinyon observed in the study area are dead, with very young (probably post-dating 2001) pinyon growing among juniper nurse trees. Pinyon were more frequent in steep rocky terrain outside of the field area. Cottonwood (*Populus fremontii*) are sparsely distributed along water courses with juniper, growing directly in the sandy ephemeral channels of small v-shaped valleys and canyons and along the floodplains of wider bottomlands. Prickly pear (*Platyopuntia spp.*), rabbitbrush (*Chysothammus spp.*) and snakeweed (*Gutierrezia sarothrea*) are abundant, as is cholla (*Cylindropuntia spp.*) near the Poshu'Owingeh room blocks and a dense artifact scatter among fields. Saltbush (*Artiplex spp.*) and yucca (*Yucca spp.*) are also common.

Study design

In this study, the application of sand and gravel mulch 400-500 years ago is conceptualized as an experimental treatment. To test whether this treatment has significant effects on soil quality, data were collected from soil profiles below mulched fields and compared to data from unmodified locations in the immediate vicinity. Because data collection was focused on well preserved agricultural features and adjacent unmodified locations, data points cluster in distinct sampling localities, which were grouped into Blocks based on soil type, vegetation characteristics, and spatial proximity. This Block design controls for ecohydrological factors that could influence the independent variables under study. Blocking is common in agricultural experiments and is technique for making uniform comparisons between treatment groups by controlling for nuisance variables that may affect variability independent of the treatment (Peterson 1994).

Sampling procedures

Soil profiles were excavated using a 4-inch (~10 cm) bucket auger with handle extensions allowing sampling depths of up to 2 meters. Soil was excavated in ca. 20 cm increments and arranged sequentially on a tarp to represent the soil profile. Bulk samples were collected with top and bottom depths to the nearest 5 cm, sealed in labeled plastic bags, and stored in a cooler, then in a refrigerator to slow bacterial metabolism and fungal growth.

Soil profiles were described in the field following conventions from Birkeland (1999) and Schoenberger et al. (2012). Soil horizons were identified and defined on the basis of disturbed soil structure, moisture and consistence, color, boundaries, roots, carbonates, and clay films. Depth to subsurface gravel was also recorded when encountered. Prior to fieldwork, the National Resource Conservation Service Web Soil Survey was consulted to define typical profile descriptions for the mapped soil units in the survey area. Colors were described in the field with a Munsell soil color chart (revised 2000). Soils were slightly moist in field condition. In some epipedons, dry soil colors were recorded and then reconciled to the moist colors recorded in similar profiles elsewhere. Hand textures were estimated in the field following Natural

Resources Conservation Service protocol modified from Thien (1979). Disturbed structure was assessed from the excavated profiles by observing the largest soil aggregates and breaking them by hand. Carbonates, roots, and clay films were described when encountered using terminology from Birkeland (1999).

Laboratory methods

Bulk soils samples were weighed in the field and sieved through 2mm mesh to quantify the coarse fraction. A 20-40 g subsample was split from the resulting fine fraction and oven dried at 60°C to measure field water content. Another sample split weighing >60 g was submitted to the Kansas State Soil Testing Laboratory for analysis of physical and chemical properties. Submitted samples were oven dried and pulverized before determining texture, soil organic matter, total carbon and nitrogen, total phosphorus, soil chloride, exchangeable cations, and pH. A summary of soil variables tested in this study and laboratory procedures are summarized in Table B.2. Further details on testing methodology are provided in Brown (1998).

Table B.2. Summary of soil variables, justification and purpose, and analytical procedures.

Analysis	Measurement purpose	Sample size	Method
Gravel content	Texture affects soil hydrology, SOM dynamics, seasonal temperature change, erosion susceptibility, leaching potential, nutrient capacity, and pH (Brady and Weil 2001).	125	Mechanical sieve
Sand, silt, clay fraction		120	Hydrometer
40th percentile particle size (D_{40})	Has a high positive correlation with infiltration rates for soils in semiarid regions (Mazaheri and Mahmoodabadi 2012).	120	Monte Carlo draws from USDA particle size ranges proportional to the textural classes measured for each sample.
Organic matter (SOM)	Reflects the net balance of biomass deposition and microbial respiration (Schmidt et al. 2011). SOM stabilizes soil aggregates and enhances soil porosity and water holding capacity (Dexter 2004).	120	Loss on ignition
Total nitrogen (N)	N and P are the most important growth limiting plant nutrients in soil, and these nutrients are linked to the turnover of SOM constituents in soil (Paul 1984).	120	Dry combustion and LECO analyzer
Available phosphorus (P_{av})		120	Melhich-3 ICP spectrometry
Cation exchange capacity (CEC)	Exchangeable Ion ratios are sensitive to water flux which promotes differential depletion of soluble species (Chadwick and Chorover 2001). Ions with higher charges and larger hydrated radii are more strongly held at exchange sites, such as Al^{3+}, and Ca^{2+}, and will accumulate relative to Na^{+} under leaching conditions (Brady and Weil 2001).	105	Unbuffered $NH_4CH_3CO_2$ extraction
Exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+})		105	Buffered $NH_4CH_3CO_2$ extraction and ICP spectrometry
Exchangeable sodium percentage (ESP)	A measure of sodicity in agricultural soils, excess sodium can harm crop yields and undermine physical soil properties (Sumner 1993). In natural ecosystems, ESP varies predictably with climate; drier sites tending to high ESP (Brady and Weil 2001: Table 8.8).	105	Na^{+} ($cmol_C\ kg^{-1}$) / $\sum$Ca2+, Mg2+, K+ ($cmol_C\ kg^{-1}$)

Statistical analysis

This study evaluates the null hypothesis that treatment (mulched or unmodified) has no effect on soil variables. After evaluating the changes in the depth of leaching intensity, a simple physical model is constructed to evaluate how different irrigation magnitudes relate to the observed changes in water flux. The purpose of this model is to conceptualize how the irrigation effects of gravel mulch and climate affect water balance.

This study uses unbalanced natural Blocks to isolate nuisance variables, and the null hypothesis for such a design is that mulch treatment has no effect in any Block (Newman et al. 1997). A Skillings-Mack rank sum test was used to evaluate whether soil variables are identically distributed between treatment groups. The Skillings-Mack test is a non-parametric statistic useful for evaluating effects in block designs with random missing data (Skillings and Mack 1981). The test was implemented using an algorithm in the "Skillings.Mack" package in the R statistical computer program. The p-value for this test is generated from Monte-Carlo draws on a Chi-squared distribution (Srisuradetchai 2015). After sampling sties were assigned to the six blocks, the significance level (α) was determined by considering simulated measurements from the same number of blocks. Finding consistently higher or lower ranks for a single measurement from five out of six blocks corresponds $\alpha \approx 0.10$ and four out of six with one tie is $\alpha \approx 0.20$. The p-value declines as ranks are replicated across the blocks. For this study, a p-value less than or equal to 0.10 is considered enough to reject the null hypothesis that a variable from two treatments is identically distributed for all blocks.

To test for a significant difference between treatment groups disregarding all other factors, a Mann-Whitney test was used to evaluate the null hypothesis that measures of a variable from T_1 and T_2 are identically distributed. The Mann-Whitney test is a non-parametric method determining the location shift between the distributions for two unpaired samples (Hollander et al. 2013). The test was implemented in the base statistics package in the R program with a p-value based on the normal approximations of the distribution of the Wilcoxon rank sum statistic and uses the subtraction method on the sum of the ranks of the first sample (R Core Team et al. 2019).

A physical model for water flux given empirical and reference soil conditions was constructed to help hypothesize the relative role of runoff and direct precipitation in gravel mulch irrigation. Such a model represents simple textbook systems with generalized parameters informed by both field observations and theoretical values (see Allen et al. 1998). The purpose is to generate a falsifiable hypothesis about how cotton agriculture functioned in the Rio Chama Basin and to highlight important aspects of the hydroclimatology of this technology. To conceptualize the effectiveness of runoff irrigation; the depth of increased leaching intensity is assumed to be equivalent to the increase in depth of water penetration or the depth (*d*) at which the percent of water in gravity flux (*P*) reaches zero. In this simple physical model *d* is the product of time ($t_{1:n}$) in hours and saturated hydraulic conductivity (K_{sat}) cm hr^{-1}, such that:

$$P_{di} = \begin{cases} \frac{P_{di-1} - (K_{sat}\ x\ (FC\ x\ BD)) - \mathrm{E}_{ti} - T_{di}}{P_{d0}}\ x\ 100, & \text{if } P_{di} > FC \\ 0, & \text{if } P_{di} < FC \end{cases} \tag{1}$$

Where: *FC* is hypothetical field capacity of the soil textural class (see Brady and Weil 2000:210; Rendig and Taylor 1969:11); BD is bulk density measured in the field during a pilot study; E_t is time dependent evaporation following Brutsaert (2014: Eq. 3 citing Black 1969), T_d is mean plant water uptake for short grass (cm day^{-1}) in moistened soil (Taylor and Klepper 1971: Table 5). K_{sat} is estimated from D_{40} following Mazaheri and Mamoodabadi (2012: Eq. 3). The term P_{d0} in Eq. 1 is the height (cm) of a column of water received by the profile.

Results

Gravel mulch fields are the predominant agricultural feature across the surveyed area. A total of 3.8 ha of gravel mulched fields was mapped within the study area. Mulched fields occur as both single garden plots and sprawling complexes of adjacent plots. Throughout the survey area,gravel mulched plots – on the order of 1-10 m^2 – form aggregates covering as much as 100-1,000 m^2. As in previous descriptions of gravel mulched fields, the increased density and vigor of grass is an obvious characteristic of these fields. Prior to soil sampling in August 2018, the study area received only 136 mm of precipitation (~40% below normal). The result was a significant soil moisture deficit that manifested as decreased vegetative growth compared to the prior year (Figure B.3). Despite the shortfall, and the resulting poor condition of grass, increased vegetation density was still apparent on mulched surfaces while extensive bare soil characterized unmodified areas.

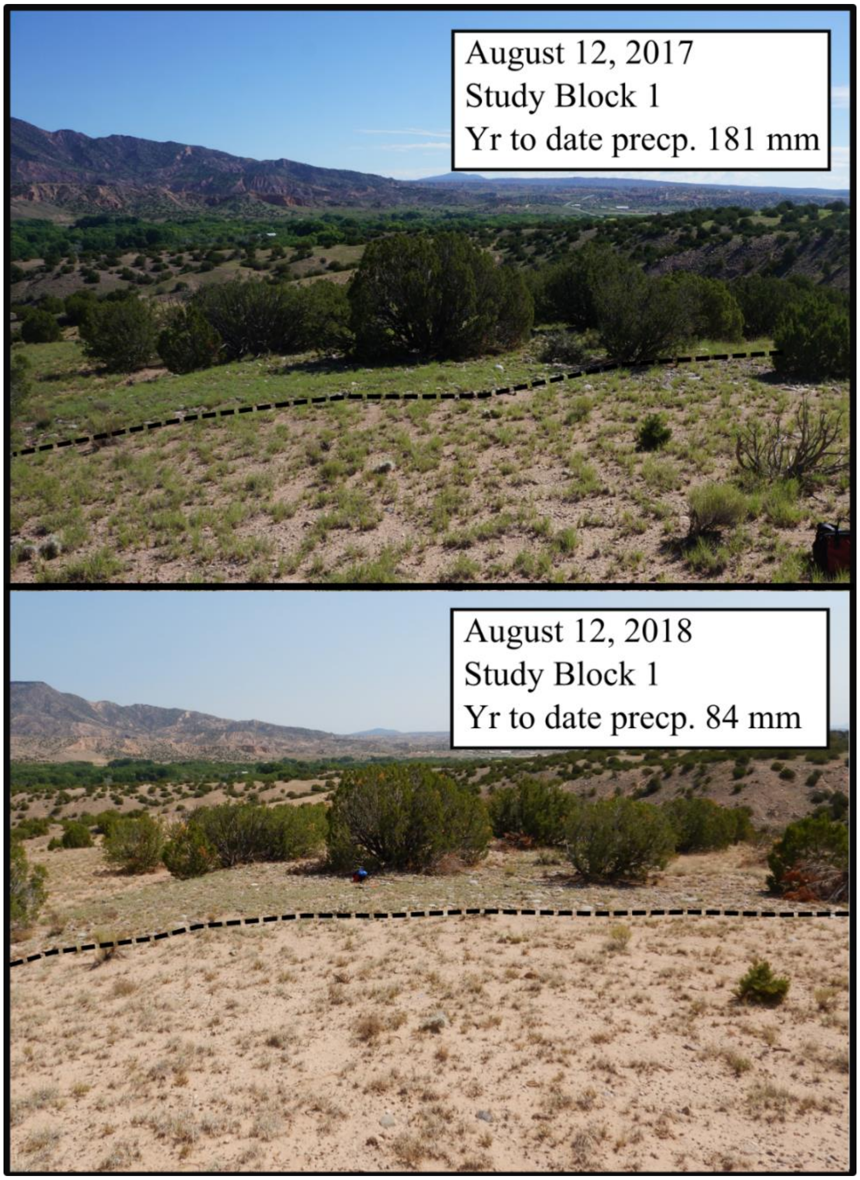

Figure B.3. Increased density and vigor of vegetative growth typical within gravel mulched fields (outlined by dashed line). Both photos were taken in Block 1 (view east-northeast) on the same date one year apart. The upper photo depicts an average precipititon year (2017) while the lower photo depicts a ~40 percent below normal year (2018). Soil sampling was conducted in 2018.

Study localities were typically associated with well drained Typic Haplustepts characterized by brown (7.5 YR 4/4) to light brown (7.5 YR 6/4) or reddish yellow (7.5 YR 6/6) sandy loam with A – Bw – Bk profiles (Soil Survey Staff 2018) (Table B.3; Figure B.4 and B.5). Soils at Block 7 and 10 graded toward Typic Haplusalfs or Ustic Haplargrids characterized by well-drained brown (7.5 YR 4/4) to light brown (7.5 YR 6/4) sandy loam with A – Bt – Btk profiles. In nearly all profiles, carbonates in Bk or Btk horizons commonly form discontinuous white coatings in macropores along with fewer fine soft nodules. The disturbed structure of Bk horizons was typically medium subangular blocks which broke with moderately hard finger pressure. Patchy clay films on medium subangular blocky ped faces distinguished Bt and Btk horizons from Bw and Bk horizons. Disturbed peds in argillic horizons typically broke with harder finger pressure and had a more plastic consistence.

Table B.3. Study Block Characteristics.

Block	No. profiles (treatment)	Soil taxonomy	Typical Profile	A horizon texture	Moisture rank[1]
1	1 (mulch), 2 (unmodified)	Typic Haplustepts	A-Bw-Bk	sandy loam	3
45	1 (basin), 3 (mulch), 3 (unmodified)	Typic Haplustepts	A-Bw-Bk	sandy clay loam	1
6	3 (mulch), 2 (unmodified)	Typic Haplustepts	A-Bw-Bk	sandy loam	2
7	3 (mulch), 2 (unmodified)	Typic Haplustalfs / Haplustepts	A-Bw-Bk/Btk	sandy loam	5
812	2 (mulch), 3 (unmodified)	Typic Haplustepts	A-Bw-Bk	sandy loam	6
10	2 (mulch), 3 (unmodified)	Ustic Haplargrids	A-Bw/Bt-Btk	sandy loam	4

[1] Moisture rank (1-6) qualifies site factors observed in the field associated with soil moisture availability: topography, vegetation, and soil texture. High number indicates more aridic.

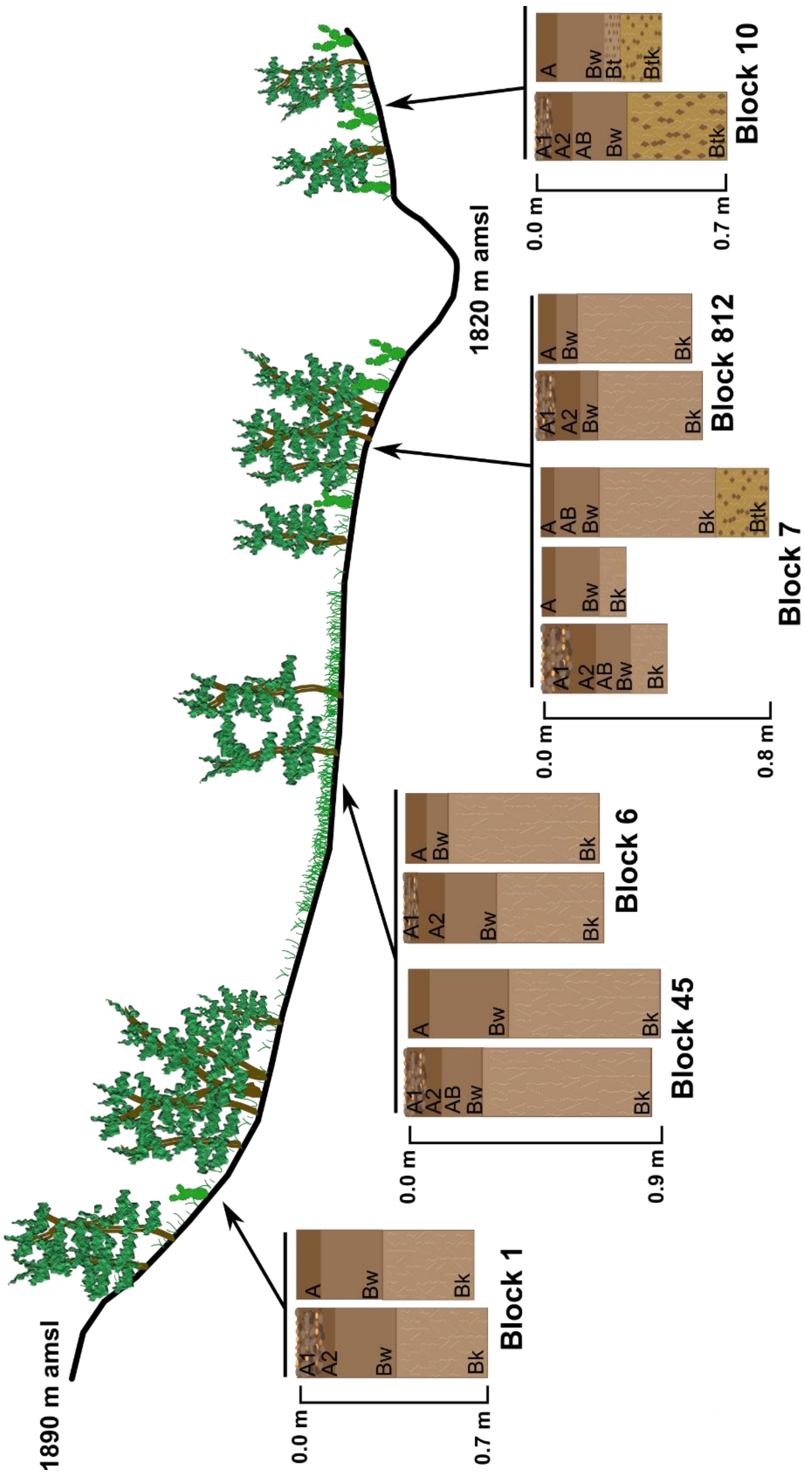

Figure B.4. Typical soil profiles from each study Block, the location of each Block along the idealized catena. Density of grass, trees, and cacti represent qualitative differences in vegetation at each study Block, with Blocks 1, 45, and 6 in typical ustic locations and Blocks 7, 812 and 10 in more aridic sites.

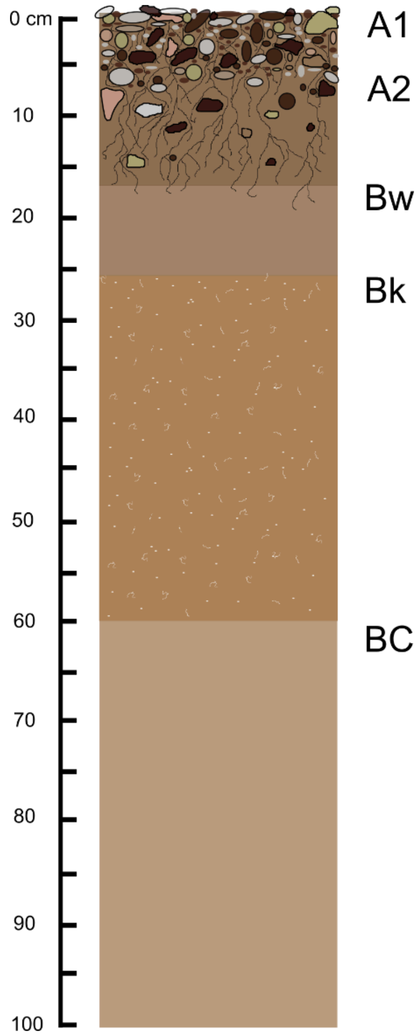

Figure B.5. Schematic profile of the typical A-Bw-Bk profile described in the gravel mulched field complexes at Poshu'Owingeh.

Many gravel mulch fields are positioned to receive surface runoff, with visible flow paths arranged along a continuum of configurations which appear to vary as a function of hillslope length. On longer sandy hillslopes, with backslope lengths approaching 100 m, rivulets converge and run parallel to lengthy rock alignments along the edge of fields (Figure B.6). On shorter hillslopes, rivulets tend to run perpendicular to rock alignments with intermittent gaps (Figure B.7). In this situation rivulets converge and form micro-fan constructions upslope of alignments.

Rock alignments are often observed independent of field borders and are usually situated in locations which apparently served to direct surface flow (Figure B.7 and B.8).

In addition to mulched fields, a shallow water collection basin, or tank, was sampled in Block 45. This feature was surrounded by slightly elevated mulched fields and was associated with an L-shaped rock alignment that apparently funneled slope wash into it (Figure B.8). The soil profile and pollen assemblage recovered from the feature suggests that it filled with approximately 20 cm of slope wash after the cessation of agriculture use (Appendix C). Channel check dams were documented in several location, and consisted of linear, partially buried arrangements of cobbles placed perpendicularly to the direction of flow (Figure B.9).

Figure B.6. Example of gravel mulch field at Poshu'Owingeh (Block 6) with active flow paths parallel to a rock border similar to those documented elsewhere in the Chama Basin (Camilli and Banet 2012). While there is no obvious indication of an excavated ditch (it may have filled) black arrows indicate the location and direction of rivulets carrying surface runoff.

Figure B.7. Example of gravel mulch field at Poshu'Owingeh (Block 7) with active flow paths perpendicular and parallel to linear rock alignments (dashed lines). Solid black arrows indicate the location and direction of rivulets carrying surface runoff. This mulched field is situated beneath a short (~15 m) hillslope with the upper half characterized by a stony surface.

Figure B.8. Basin feature in Block 45. Arrows indicate the dip and contour of the surrounding landscape relative to the basin depression. Thick dashed line outlines a rock alignment bordering a gravel mulched field. Bucket auger beyond blue tarp measures 1.8 m in length. Photo is from the east edge of the feature; view is to the west-northwest.

Figure B.9. Example of cobble, channel check dam, impounding sediment west of Block 6. The exposed portion of the feature is approx. 2 meters in length.

Significant effects on soil attributes associated with gravel mulch are confined to surface soil horizons (A, AB, and upper centimeters of the Bw). For most soil variables analyzed, site factors have larger effects than gravel mulch treatment (Table B.4). Ranked measurements of particle size distribution (D_{40}), Mg^{2+}, Na^{2+}, and ESP are significantly different between sampled treatments, but of these variables, only differences in D_{40} are consistent across Blocks. The distribution of ranked measurements of P_{av} and CEC were not significantly different between treatments, but the small change observed between treatments was consistent across Blocks. Gravel mulch significantly increases surface soil particle size by the addition of gravelly sand over the A horizon. Concentrations of exchangeable base ions Mg^{2+} and Na^{+}, are generally reduced beneath mulch but site factors determining soil moisture availability also have an effect The small reduction in CEC associated with gravel mulch, which is consistent across Blocks, could be driven by losses of Mg^{2+} and Na^{+}. The magnitude and direction of change in Na^{+} and the ratio of Na^{+} to other base nutrients (ESP) suggests that Na^{+} levels are especially sensitive to the effects of gravel mulch and soil moisture. P_{av} responds to both site factors and gravel mulch to a similar degree, and together with change in the most mobile base cation (Na^{+}) suggests a positive feedback between site factors controlling soil moisture and gravel mulch that control water flux through the profile.

Table B.4A. Summary of the effects of mulch treatment and site factors in surface soils.

Variable	Average values by treatment and site factors				Effect (%)		Significance[3]
	Mulch	*Unmodified*	*Moist*	*Aridic*	*Mulch*[1]	*Site*[2]	
D_{40} (mm)	0.77	0.16	0.41	0.61	125%	-41%	D*
A thickness (cm)	7.3	7.5	7.7	7.2	-2%	7%	--
Water (%)	5.38	5.01	7.72	3.97	7%	68%	--
SOM (%)	1.14	1.04	1.35	0.96	9%	35%	--
N (mg L^{-1})	710	749	780	732	-5%	6%	--
C:N	8.5	8.0	9.6	6.9	7%	33%	--
P_{av} (mg L^{-1})	14	12	16	13	20%	20%	*
Clay (%)	16	18	19	16	-15%	14%	--
CEC ($cmol_C$ kg^{-1})	20	23	21	22	-11%	-5%	*
Soil pH	8.4	8.4	8.3	8.4	0%	-2%	--
Ca (mg L^{-1})	3499	3821	3512	3793	-9%	-8%	--
Mg (mg L^{-1})	239	306	313	240	-24%	27%	D
K (mg L^{-1})	183	188	200	173	-2%	14%	--
Na (mg L^{-1})	85	115	53	139	-30%	-88%	D
ESP (%)	59.8	110.7	49.7	113.6	-61%	-77%	D

Table B.4B. Summary of the effects of mulch treatment and site factors in subsoils.

Variable	Average values by treatment and site factors				Mean effect (%)		Significance
	Mulch	*Unmodified*	*Moist*	*Aridic*	*Mulch*	*Site*	
D_{40} (mm)	0.17	0.21	0.19	0.22	-22%	-13%	--
Bk depth (cm)	22.8	22.6	29.0	20.2	1%	37%	--

Water (%)	5.83	5.82	5.47	6.12	0%	-11%	--
SOM (%)	0.78	0.78	0.90	0.66	0%	30%	--
N (mg L^{-1})	601	613	622	587	-2%	6%	--
C:N	8.1	8.6	9.3	6.9	-6%	30%	--
P_{av} (mg L^{-1})	9	9	7	12	-1%	-49%	--
Clay (%)	22	21	22	22	3%	4%	--
CEC ($cmol_C$ kg^{-1})	29	31	26	34	-7%	-27%	--
Soil pH	9	9	8	9	-1%	-4%	--
Ca (mg L^{-1})	4351	4436	4033	4780	-2%	-17%	--
Mg (mg L^{-1})	478	463	487	403	3%	18%	--
K (mg L^{-1})	176	156	159	183	12%	-14%	--
Na (mg L^{-1})	691	1142	277	1511	-50%	-136%	--
ESP (%)	678.3	1113.1	263.8	1484.2	-49%	-138%	--

[1] Effect of mulch = (Mulch - Unmodified) / [(Mulch + Unmodified + Moist + Aridic) / 4]

[2] Effect of moisture= (Moist - Aridic) / [(Mulch + Unmodified + Moist + Aridic) / 4]

[3] D = Significant difference between treatments (Mann-Whitney p-value ≤ 0.10), * = Consistent difference across Blocks (Skillings-Mack p-value ≤ 0.10)

Gravel mulch is 9 cm thick on average and is similarly thick in both mesic and xeric study Blocks. A horizon thickness in mulched treatments (7.3 cm excluding mulch in the A horizon) is similar to unmodified profiles (mean = 7.5 cm), an insignificant (Mann-Whitney p-value < 0.10) difference that is not consistent between blocks (Skillings-Mack p-value > 0.1) (Table B.5). The difference in A horizon thickness between treatments increases if placed sand and gravel is included in the A horizon thickness of mulched profiles (mean = 16 cm). The basin feature in Block 45 has the thickest A horizon in any profile recorded in the study area (23 cm). Secondary carbonates (Bk horizon) are at similar depths beneath mulch treatments (22.8 cm below the A1 horizon) compared to unmodified profiles (22.6 cm below surface), an insignificant difference which is not consistent between Blocks (Skillings-Mack p-value > 0.10). The difference remains insignificant when mulch thickness is added back to the Bk depth under mulched treatments.

Table B5. Summary horizon depths

Location	Treatment	No. profiles	Thickness (cm)			Depth (cm)	
			A horizon	*Mulch*	*Difference*	*Bk horizon*	*Difference*
Block 1	Mulch	2	14	10	4	37	27
	Unmodified	2	9			37	
Block 45	Mulch	3	18	9	9	38	29
	Basin	1	23			NA	
	Unmodified	3	8			38	
Block 6	Mulch	3	14	6	8	33	27
	Unmodified	2	8			16	
Block 7	Mulch	3	20	12	8	20	8
	Unmodified	2	5			20	
Block 812	Mulch	2	16	8	8	26	18
	Unmodified	3	7			15	
Block 10	Mulch	2	14	7	7	35	28
	Unmodified	2	8			32	

Particle size determination was intended to substantiate working models for the effect of mulch on infiltration and water retention. Lithic mulch recorded in this study consists of gravelly to extremely gravelly sandy loam with 35 to 95 percent coarse fraction. Unsurprisingly, average A horizon gravel content is substantially and consistently higher in mulched treatments (mean = 41%) than unmodified treatments (mean = 3%) (Skilling-Mack p-value = 0.01, Mann-Whitney p-value < 0.01) (Table B.6A). Gravel content in the subsoil is higher in mulched treatments (mean = 4.3%) compared to unmodified profiles (mean = 3.4 %) in 5 out 6 blocks (Skillings-Mack p-value = 0.10), but the distribution of ranks for the entire dataset is not significantly different between treatments (Mann-Whitney p-value = 0.61) (Table B.6B). Sand and silt percentage in the fine fraction was similar (within 5%) in the surface horizons of both treatments. Clay content was higher in unmodified surface horizons in 4 of 6 Blocks (Skilling-Mack p-value >0.10) for an average difference of 15 percent, but the distribution of ranks across Blocks is not significantly different (Mann-Whitney p-value > 0.10). The high concentration of coarse fragments in the A horizon skews the 40th percentile of particle size (D_{40}) toward significantly higher values in mulched treatments (0.77 mm) compared to unmodified profiles (0.16 mm) (Skillings-Mack p-value = 0.01, Mann-Whitney p-value < 0.01). More xeric Blocks had somewhat coarser D_{40} measures in the A horizon, indicating that their unmodified surfaces are better drained, but the 130 percent increase in D_{40} associated with gravel mulch attests to the significant impact of placed gravel mulch on surface horizons (Figure B.10A). Interestingly, the subsoils of mulched treatments tend to be finer than unmodified profiles, an average decrease in D_{40} of 23 percent, but the difference is not consistent between Blocks (Skilling-Mack p-value >0.10) and distribution of the ranks of across Blocks is not significantly different (Mann-Whitney p-value > 0.10). The Basin feature of Block 45 had the smallest D_{40} particle size in the A horizon of any profile (0.03 mm) due to the accumulation of fine slope wash.

Table B.6A. Particle size distribution in surface horizons

Location	Treatment	Sample size	Coarse fraction (%)			Fine fraction % sand			Fine fraction % silt			Fine fraction % clay		
			Mean	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*
Block 1	Mulch	7	38	2	67	65	54	70	19	16	26	16	14	20
	Unmodified	10	5	0	14	60	48	66	22	16	28	19	14	24
Block 45	Mulch	5	47	36	59	69	66	72	14	12	18	16	14	20
	Basin	2	0	0	0	52	50	54	25	24	26	23	22	24
	Unmodified	3	5	2	11	66	60	70	13	12	14	21	16	26
Block 6	Mulch	6	25	1	56	71	62	78	13	8	18	16	14	20
	Unmodified	3	2	1	4	66	52	82	13	8	18	21	10	30
Block 7	Mulch	4	49	16	93	69	68	70	15	14	16	16	14	18
	Unmodified	2	3	3	4	75	74	76	10	10	10	15	14	16
Block 812	Mulch	4	34	2	83	65	48	80	18	4	26	18	14	26
	Unmodified	2	1	1	2	71	54	88	12	2	22	17	10	24
Block 10	Mulch	4	55	33	95	79	76	82	9	6	10	13	12	14
	Unmodified	9	1	0	2	68	66	70	13	12	14	19	16	22

Table B.6B. Particle size distribution in subsoil

Location	Treatment	Sample size	Coarse fraction (%)			Fine fraction % sand			Fine fraction % silt			Fine fraction % clay		
			Mean	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*
Block 1	Mulch	4	5	2	9	54	44	60	25	22	32	22	18	24
	Unmodified	4	4	2	9	56	44	66	21	16	28	24	16	38
Block 45	Mulch	4	13	5	28	58	54	60	19	16	22	24	20	28
	Basin	1	26			58			16			26		
	Unmodified	5	7	4	14	58	36	66	20	8	38	23	16	28
Block 6	Mulch	7	2	1	6	67	44	80	15	6	30	18	4	26
	Unmodified	6	2	1	4	64	54	74	15	6	24	21	12	30
Block 7	Mulch	5	4	1	8	69	64	76	12	10	16	19	14	26
	Unmodified	9	6	0	19	58	20	88	20	2	46	22	10	44
Block 812	Mulch	4	1	0	1	41	30	56	36	24	46	23	10	32
	Unmodified	5	0	0	2	70	48	90	15	2	28	15	8	26
Block 10	Mulch	5	2	0	4	57	42	66	16	10	22	26	16	48
	Unmodified	5	1	0	3	48	36	76	29	4	40	23	20	24

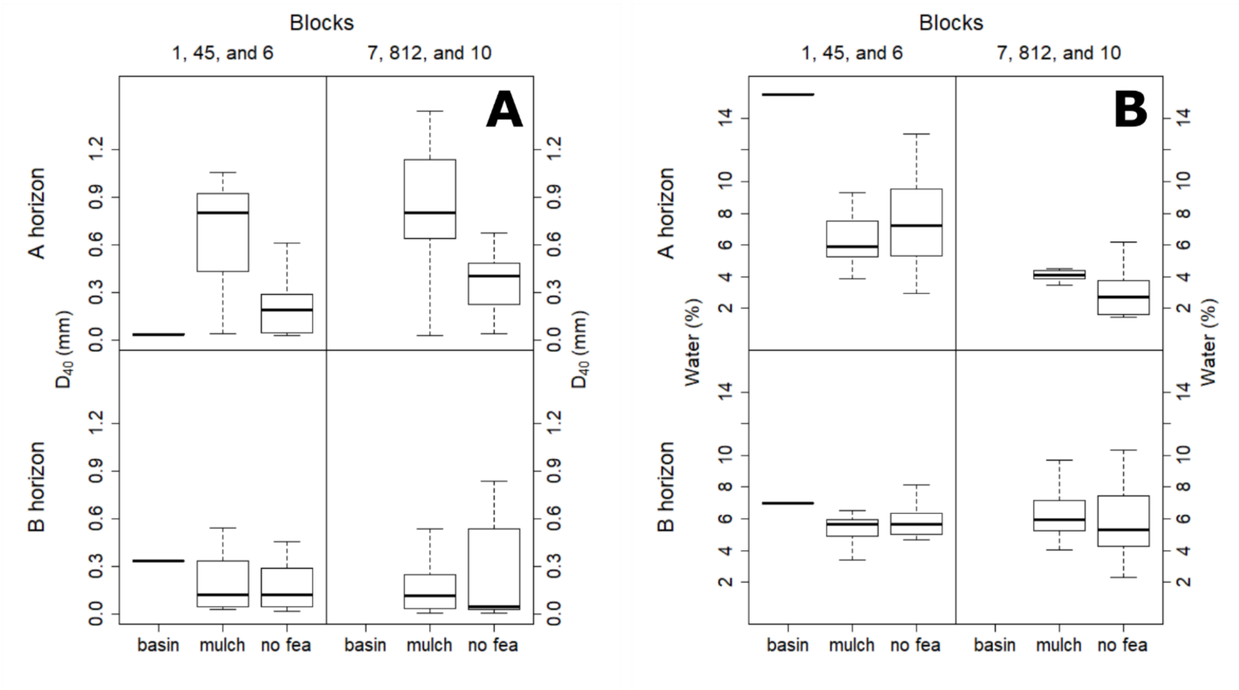

Figure B.10. Distribution of D_{40} particle size and water content between treatments among more mesic Blocks (1, 45, and 6) and more xeric Blocks (7, 812, and 10).

Soils in field condition were slightly moist in their sub horizons. In more xeric study Blocks, the upper 10 cm of soil was dry by the end of the week-long field session. Subjectively, the top of the B horizon in mulched profiles appeared slightly wetter, indicated mainly by cooler temperatures in the hand, slightly darker colors, and less friable consistence. Across treatments, water content on a dry weight basis of the fine fraction is higher in more mesic Blocks (7.7%) compared to the more xeric group (4.0%) (Figure B.7, Figure B.10b). However, water content in the fine fraction of mulched profiles (5.4%) is only fractionally larger than unmodified treatments (5.0%) and insignificant in difference (Mann-Whitney p-value >0.10) which is not consistent across blocks (Skilling-Mack p-value >0.10). Due to the high rock fraction at the surface of mulched treatments, water content on a whole basis (gravel adjusted) is much smaller

(3.2%) than unmodified treatments, a significant difference that is consistent between all Blocks (Skillings-Mack p-value = 0.01).

Table B.7A. Gravimetric water content (%) in surface horizons.

Location	Treatment	Sample size	Whole soil			Fine fraction		
			mean	*min*	max	*mean*	*min*	max
Block 1	Mulch	7	4.6	2.0	9.1	7.4	5.5	9.3
	Unmodified	10	8.5	4.7	12.0	9.1	4.8	13.0
Block 45	Mulch	5	3.3	3.0	3.8	6.4	4.9	8.1
	Basin	2	15.5	15.5	15.6	15.5	15.5	15.6
	Unmodified	3	6.3	5.6	7.1	6.7	5.8	8.0
Block 6	Mulch	6	3.7	1.9	5.1	5.1	3.9	7.5
	Unmodified	3	3.9	2.8	4.4	3.9	2.9	4.5
Block 7	Mulch	4	2.1	0.3	3.4	4.0	3.8	4.1
	Unmodified	2	3.5	3.5	3.6	3.7	3.6	3.7
Block 812	Mulch	4	3.4	1.2	6.9	5.4	3.5	7.0
	Unmodified	2	4.4	2.8	6.0	4.5	2.8	6.2
Block 10	Mulch	4	1.8	0.2	2.6	4.0	3.9	4.3
	Unmodified	9	3.4	2.7	3.8	2.2	1.4	3.9

Table B.7B. Gravimetric water content (%) in subsoil.

Location	Treatment	Sample size	Whole soil			Fine fraction		
			mean	*min*	max	*mean*	*min*	max
Block 1	Mulch	4	6.5	5.4	9.3	6.8	5.7	9.8
	Unmodified	4	6.1	4.4	7.7	6.4	4.7	8.1
Block 45	Mulch	4	5.3	4.7	6.0	6.1	5.8	6.5
	Basin	1	5.2			7.0		
	Unmodified	5	5.6	4.7	6.2	6.1	5.1	6.6
Block 6	Mulch	7	4.5	3.2	5.5	4.5	3.4	5.5
	Unmodified	6	5.1	4.5	5.8	5.2	4.7	5.9
Block 7	Mulch	5	5.4	4.1	6.4	5.6	4.3	6.5
	Unmodified	9	8.5	3.2	18.0	8.8	4.0	18.0
Block 812	Mulch	4	6.7	4.4	9.3	6.7	4.4	9.4
	Unmodified	5	4.3	2.3	7.4	4.3	2.3	7.5
Block 10	Mulch	5	6.6	4.0	9.3	6.7	4.0	9.7
	Unmodified	5	5.3	4.5	6.2	5.4	4.5	6.2

Upper soil horizons across treatments in more mesic sites have on average 64 percent more soil water than more xeric sites. This corresponds to an average increase of 34 percent in SOM in the surface horizons of profiles across treatments in mesic study Blocks (Table B.8A, Figure B.11). The fine fraction of mulched surface horizons across Blocks have slightly more

(1.1%) SOM than in unmodified profiles (1.0%), an insignificant difference (Mann-Whitney p-value > 0.10) that is not consistent between Blocks (Skilling-Mack p-value >0.10). On a whole soil basis, the difference is reversed, with mulched surface horizons having an average of only 0.7 percent SOM. The subsoils of all profiles across treatments have an average SOM content of 0.9 percent in more mesic Blocks while more xeric Blocks have subsoil SOM contents averaging 0.7 percent (Table B.8B). Across Blocks, mulched and unmodified subsoils have the same SOM content (0.8%). The basin feature of Block 45 has high A horizon SOM content (2.2%) due to its topographic position which receives organic rich run-off.

Table B.8A. Soil organic matter (%) in surface horizons.

Location	Treatment	Sample size	Whole soil *mean*	Whole soil *min*	Whole soil max	Fine fraction *mean*	Fine fraction *min*	Fine fraction max
Block 1	Mulch	7	0.72	0.43	1.10	1.205	1.04	1.45
	Unmodified	10	1.23	0.86	1.71	1.309	0.96	1.87
Block 45	Mulch	5	0.70	0.53	0.93	1.32	1.20	1.50
	Basin	2	2.20	2.10	2.30	2.20	2.10	2.30
	Unmodified	3	1.29	1.26	1.34	1.3667	1.30	1.50
Block 6	Mulch	6	0.82	0.44	1.35	1.0683	0.90	1.40
	Unmodified	3	0.99	0.75	1.20	1.0133	0.78	1.21
Block 7	Mulch	4	0.51	0.07	0.74	1.0425	0.60	1.30
	Unmodified	2	0.63	0.58	0.67	0.65	0.60	0.70
Block 812	Mulch	4	0.85	0.27	1.38	1.38	0.96	1.60
	Unmodified	2	0.79	0.60	0.98	0.8	0.60	1.00
Block 10	Mulch	4	0.36	0.04	0.53	0.8	0.80	0.80
	Unmodified	9	1.09	0.69	1.50	1.1	0.70	1.50

Table B.8B. Soil organic matter (%) in subsoil.

Location	Treatment	Sample size	Whole soil *mean*	Whole soil *min*	Whole soil max	Fine fraction *mean*	Fine fraction *min*	Fine fraction max
Block 1	Mulch	4	1.02	0.88	1.09	1.0675	0.90	1.20
	Unmodified	4	0.94	0.78	1.15	0.9825	0.80	1.20
Block 45	Mulch	4	0.98	0.70	1.32	1.15	0.80	1.60
	Basin	1	0.89			1.20		
	Unmodified	5	1.12	0.86	1.33	1.2	0.90	1.40
Block 6	Mulch	7	0.65	0.45	0.86	0.6586	0.45	0.87
	Unmodified	6	0.69	0.48	1.00	0.7	0.50	1.03
Block 7	Mulch	5	0.62	0.32	0.86	0.644	0.32	0.90
	Unmodified	9	0.56	0.32	0.94	0.5856	0.33	1.00
Block 812	Mulch	4	0.72	0.49	0.90	0.725	0.50	0.90
	Unmodified	5	0.56	0.30	0.70	0.56	0.30	0.70
Block 10	Mulch	5	0.68	0.49	1.05	0.7	0.50	1.10
	Unmodified	5	0.83	0.48	1.30	0.84	0.50	1.30

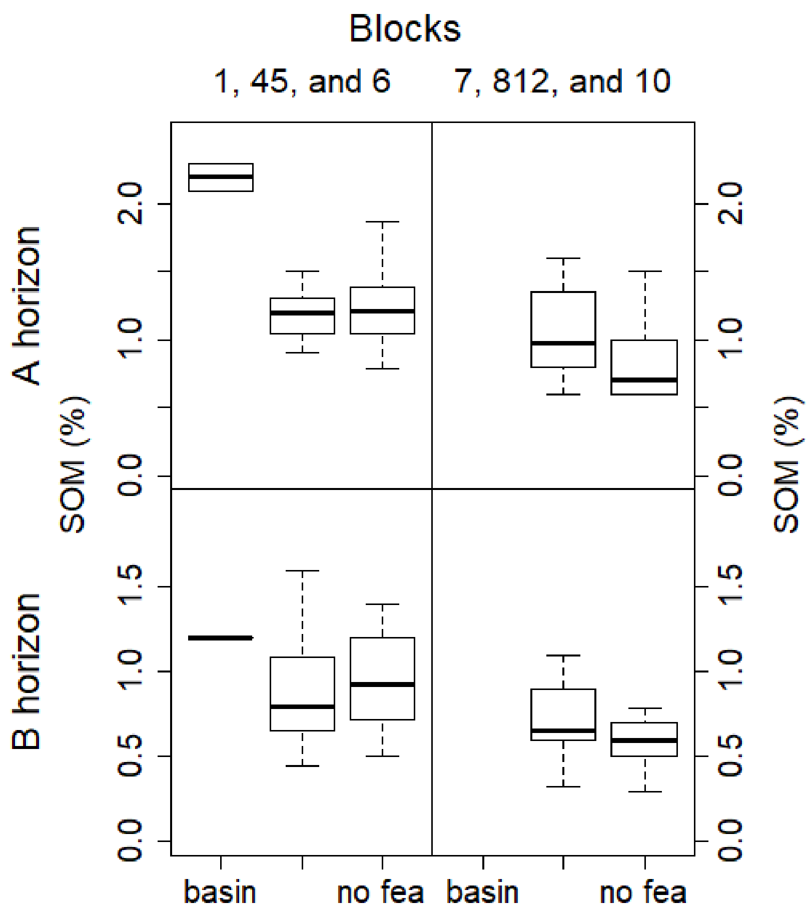

Figure B.11. Distribution of soil organic matter in more mesic (Blocks 1, 45, and 6) and more xeric sites (Blocks 7, 812, and 10) by treatment. Note that the only basin feature analyzed in this study was from Block 45, the most mesic locations.

Soil nutrients and exchangeable cations are presented here as mass per liter of soil solution (mg L^{-1}) and so are only discussed for the soil fine fraction. The surface horizons of profiles across treatments in more mesic Blocks have slightly higher average total N levels (780 mg L^{-1}) than more xeric Blocks (732 mg L^{-1}) (Table B.9A, Figure B.12). Mulched profiles across Blocks have slightly lower average total N levels (710 mg L^{-1}) than surface horizons in unmodified treatments (749 mg L^{-1}), and insignificant difference (Mann-Whitney p-value > 0.10) that is not consistent between Blocks (Skilling-Mack p-value >0.10). As with the surface horizons, the subsoils of profiles across treatments in more mesic Blocks have slightly higher total N levels (622 mg L^{-1}) than more xeric Blocks (587 mg L^{-1}), while mulched treatments across Blocks have similar total N levels (601 mg L^{-1}) than unmodified treatments (613 mg L^{-1}) (Table B.9B). The basin feature of Block 45 has high total N levels (1100 mg L^{-1}) that are similar to the mean N levels of unmodified profiles from the same Block. P_{av} is similar in the surface horizons below mulch (14 mg L^{-1}) than below unmodified profiles (12 mg L^{-1}). This difference is consistent for all locations except Block 1 (Skillings-Mack p-value = 0.10) (Table B.9A, Figure B.13). For the subsoil, average P_{av} is the same between treatments across Blocks (9 mg L^{-1}) but differs between mesic and xeric Blocks (7 and 12 mg L^{-1} respectively). C:N ratios in surface horizons are increased in qualitatively more moist sites (9.6) compared to more aridic sites (6.9), a larger increase than that associated with treatment (8.5 for gravel mulch, 8.0 for unmodified).

Table B.9A. Total nitrogen, available phosphorus, and carbon:nitrogen ratio in surface horizons.

Location	Treatment	Sample size	N (mg L^{-1})			P_{av} (mg L^{-1})			C:N		
			mean	*min*	max	*mean*	*min*	max	*mean*	*min*	max
Block 1	Mulch	7	533	200	900	11	4	18	13.7	7.2	26.0
	Unmodified	10	560	300	1000	15	5	27	12.4	8.1	16.7
Block 45	Mulch	5	800	700	900	20	6	53	8.3	8.1	8.6
	Basin		1100	1100	1100	37	22	52	10.0	9.5	10.5
	Unmodified	3	1200	900	1600	7	6	8	5.9	4.7	7.2
Block 6	Mulch	6	733	600	1000	12	3	24	7.3	6.9	8.3
	Unmodified	3	533	400	700	11	7	13	9.9	7.8	13.1
Block 7	Mulch	4	775	500	1000	16	11	21	6.7	6.0	7.2
	Unmodified	2	800	500	1100	12	12	13	4.6	3.2	6.0
Block 812	Mulch	4	850	800	900	14	6	26	8.2	5.3	10.0
	Unmodified	2	650	500	800	11	11	12	6.9	3.8	10.0
Block 10	Mulch	4	567	500	600	14	11	17	7.1	6.7	8.0
	Unmodified	9	750	600	900	13	8	17	8.2	3.9	12.5

Table B.9B. Total nitrogen, available phosphorus, and carbon:nitrogen ratio in subsoil.

Location	Treatment	Sample size	N (mg L^{-1})			P_{av} (mg L^{-1})			C:N		
			mean	*min*	max	*mean*	*min*	max	*mean*	*min*	max
Block 1	Mulch	4	625	300	900	5	3	6	11.6	7.1	20.7
	Unmodified	4	525	300	800	4	1	8	11.9	8.7	18.0
Block 45	Mulch	4	750	600	1000	8	6	10	8.8	7.7	11.6
	Basin	1	1100			10			6.3		
	Unmodified	5	1000	500	1400	7	1	17	7.4	5.4	10.4
Block 6	Mulch	7	457	400	600	10	2	24	8.4	6.5	10.2
	Unmodified	6	417	200	600	7	1	16	10.8	5.8	18.0
Block 7	Mulch	5	660	300	1000	10	7	17	6.1	3.5	8.1
	Unmodified	9	444	300	600	17	12	25	7.6	5.8	11.6
Block 812	Mulch	4	775	600	1100	10	2	15	5.5	4.1	7.5
	Unmodified	5	640	400	900	11	1	18	5.2	3.9	7.0
Block 10	Mulch	5	520	400	800	13	2	21	8.1	5.1	10.6
	Unmodified	5	560	400	900	10	4	16	8.7	7.3	11.6

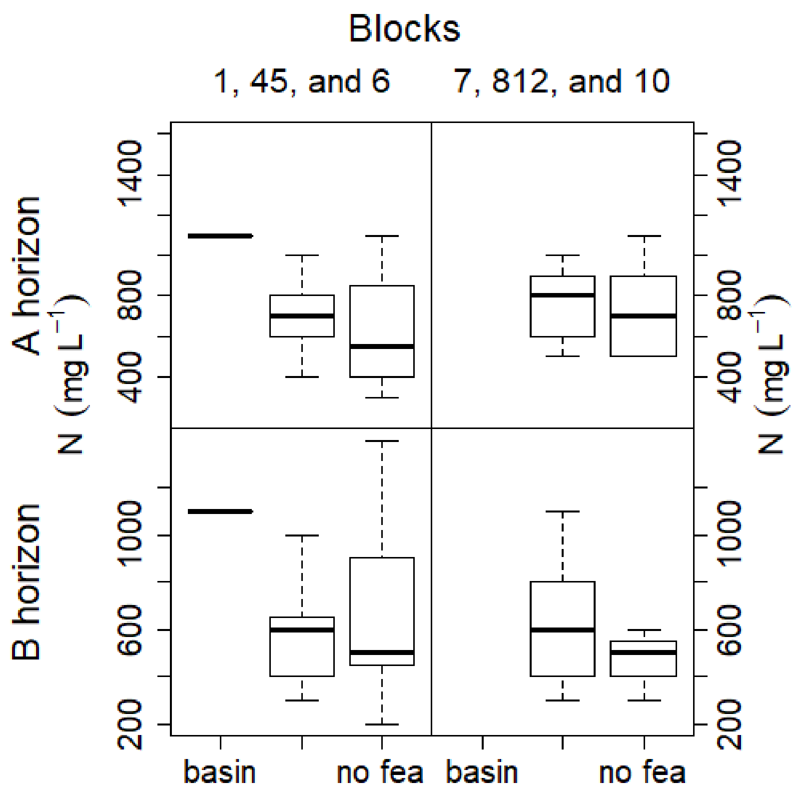

Figure B.12. Distribution of soil total nitrogen in more mesic (Blocks 1, 45, and 6) and more xeric sites (Blocks 7, 812, and 10) by treatment. Note that the only basin feature analyzed in this study was from Block 45, the most mesic locations.

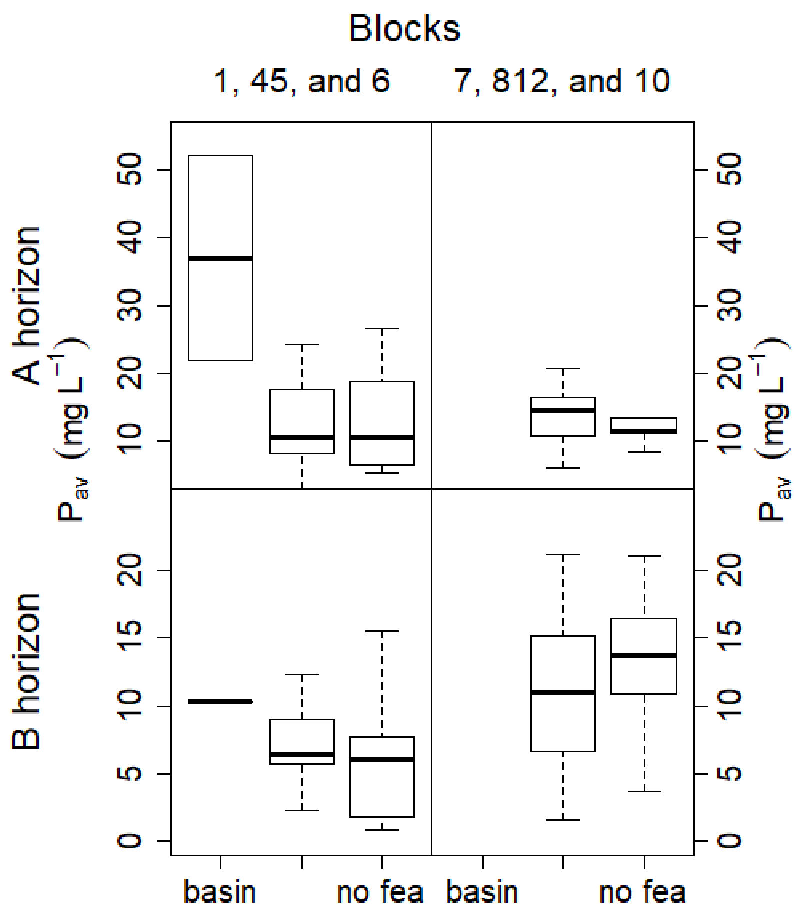

Figure B.13. Distribution of available phosphorus in more mesic (Blocks 1, 45, and 6) and more xeric sites (Blocks 7, 812, and 10) by treatment. Note that the only basin feature analyzed in this study was from Block 45, the most mesic locations.

Ratios of relatively immobile (Ca^{2+}) and readily leached (Na^{+}) base ions are indicative of changes in water flux beneath gravel mulch fields. Both the treatment and site characteristics influence Na^{+} leaching, with treatment having more influence on leaching intensity of the upper soil horizons (I base on ESP). The relative effect sizes of ESP in the surface horizons and subsoils as well as the depth profiles of Ca^{2+}/Na^{+} show that mulch treatment enhances water flux in the upper 50 cm of the profile and that the effect is enhanced in mesic locations.

Average cation exchange capacity is lower in the surface horizons of mulched profiles in every study Block (Skillings-Mack p-value = 0.01) but the difference is modest (-11%) and the distribution of ranks across the dataset is not significantly different (Mann-Whitney p-value > 0.10) (Table B.10A). The magnitude of the decrease in the CEC is similar to the decrease in clay content of surface horizons and could be due to the artificial increase in the sand percentage of the fine fraction due to the placement of mulch. The difference in CEC between treatments across blocks narrows somewhat in the subsoil (7% less in mulched profiles) and is much less that the average difference between mesic and xeric Blocks (28% less in mesic Blocks).

Table B.10A. Cation exchange capacity and counting base nutrients in surface horizons.

Location	Treatment	Sample size	Total CEC ($cmol_C$ kg^{-1})			Ca (mg L^{-1})			Mg (mg L^{-1})			K (mg L^{-1})		
			mean	*min*	*max*	*mean*	*min*	*max*	*mean*	*min*	*max*	*mean*	*min*	*max*
Block 1	Mulch	7	20	19	22	3448	3320	3575	318	220	416	160	158	162
	Unmodified	10	23	23	23	4047	4047	4047	286	286	286	177	177	177
Block 45	Mulch	5	19	17	22	3292	2683	3924	268	198	352	191	156	213
	Basin	2	21	21	21	3423	3277	3569	360	283	436	216	197	235
	Unmodified	3	21	18	25	3197	2857	3679	426	309	605	314	239	410
Block 6	Mulch	6	21	20	21	3597	3229	3755	246	180	360	174	154	204
	Unmodified	3	22	16	25	3581	2361	4272	287	123	377	168	141	202
Block 7	Mulch	4	21	18	25	3367	2975	3554	199	152	249	173	145	205
	Unmodified	2	21	21	22	3516	3429	3603	286	283	290	142	125	159
Block 812	Mulch	4	21	19	25	3721	3384	4446	234	179	298	243	212	266
	Unmodified	2	26	15	36	4729	2566	6893	157	128	185	169	117	221
Block 10	Mulch	4	20	18	21	3570	3315	3756	168	143	211	157	136	171
	Unmodified	9	23	22	25	3855	3765	3944	393	254	532	156	141	171

Table B.10B. Cation exchange capacity and counting base nutrients in subsoil horizons.

Location	Treatment	Sample size	Total CEC ($cmol_C$ kg^{-1})			Ca (mg L^{-1})			Mg (mg L^{-1})			K (mg L^{-1})		
			mean	*min*	*max*	*mean*	*min*	*max*	*mean*	*min*	*max*	*mean*	*min*	*max*
Block 1	Mulch	4	25	24	25	3655	3474	3792	655	526	768	137	117	148
	Unmodified	4	26	23	29	3692	3468	3971	548	298	761	88	55	144
Block 45	Mulch	4	24	23	25	4022	3823	4267	400	294	494	186	119	261
	Basin	1	23			4192			182			219		
	Unmodified	5	25	20	27	3620	3105	3959	529	363	680	222	115	313
Block 6	Mulch	7	24	22	27	3696	3540	3889	528	305	738	129	80	184
	Unmodified	6	34	25	66	5353	3344	11765	566	493	770	131	101	169
Block 7	Mulch	5	27	20	37	4029	3035	4679	284	195	335	180	151	208
	Unmodified	9	51	19	117	6037	2635	15076	268	176	379	235	88	408
Block 812	Mulch	4	43	32	63	5971	3455	10923	509	239	805	252	209	330
	Unmodified	5	26	17	44	4133	2814	8115	309	253	416	141	90	194
Block 10	Mulch	5	33	22	52	4732	3489	8074	489	292	719	169	119	203
	Unmodified	5	26	24	29	3779	3509	4074	556	371	696	118	65	137

Measured Ca^{2+}, Mg^{2+}, and K^{2+} in agricultural soil levels do not significantly vary between Blocks or treatments (Figure B.14). Across treatments, mesic Blocks have higher average Mg^{2+} levels (313 mg $^{-1}$) compared to more xeric blocks (240 mg L^{-1}) with a proportional decline in Mg^{2+} in mulched treatments (239 mg L^{-1}) compared to unmodified profiles (306 mg L^{-1}), which corresponds to a suggestive level of difference between the data ranks (Man-Whitney p-value = 0.10). Across treatments, surface horizons in mesic Blocks have slightly higher exchangeable K^+ content (200 mg L^{-1}) compared to unmodified treatments (173 mg L^{-1}), a much larger difference than between treatments across Blocks which are very similar in K^+ content (only 2% less under mulch) (Figure B.14C). A somewhat larger gap between treatments is observed in subsoil K^+ content, where mulched treatments have 12 percent more exchangeable K^+ (176 mg L^{-1}) compared to unmodified profiles (156 mg L^{-1}) though the distribution of ranks across all Block and treatments is not significantly different (Mann-Whitney p-value >0.10) and the difference is not consistent across ranks (Skilling-Mack p-value >0.10).

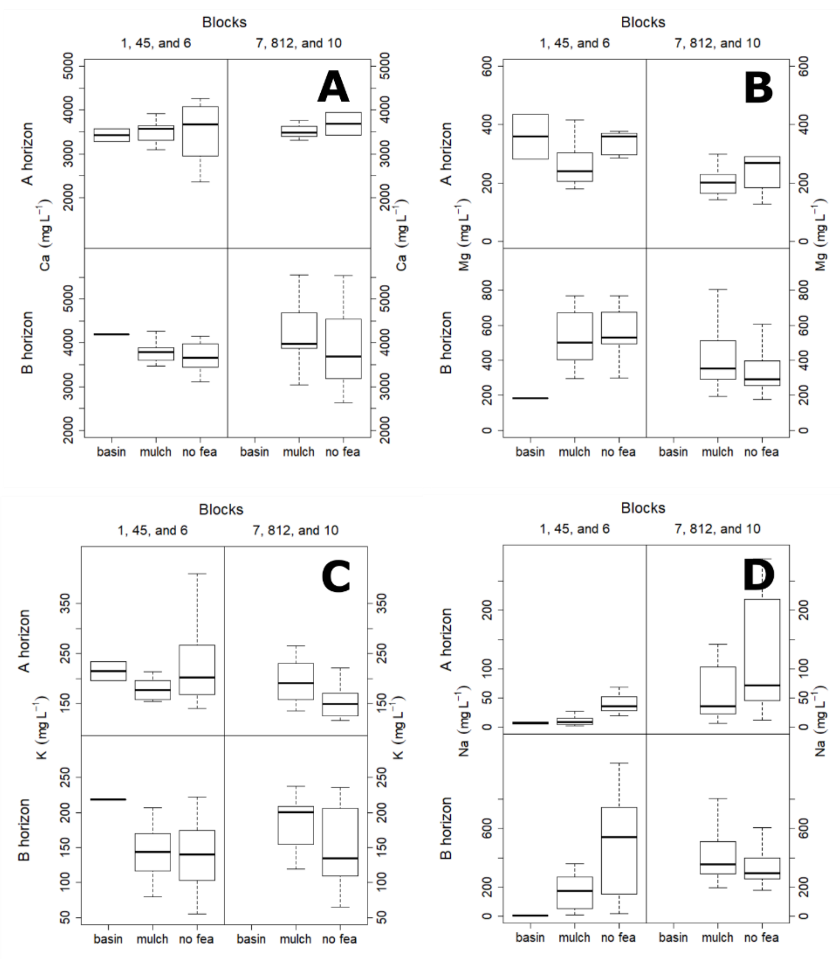

Figure B.14. Distribution of base cations, Ca^{2+} (A), Mg^{2+} (B), K^+ (C), and Na^+ (D) between treatments and more mesic Blocks (1, 45, and 6) and more xeric Blocks (7, 812, 10).

Exchangeable Na^+ content is significantly different between treatments, with mulched surface horizons averaging 85 mg L^{-1} compared to 115 mg L^{-1} in unmodified surface horizons (Figure 14D). While the difference in ranks across the dataset is significant (Mann-Whitney p-value = 0.01), it is not consistent across blocks (Skilling-Mack p-value >0.10) and the difference is smaller than between mesic and xeric Blocks (90% less Na in mesic Blocks). The major differences in Na^+ levels are mirrored in ESP, but the magnitude of the differences between mulched and unmodified treatments in magnified (Table B.11). For ESP in surface horizons, the effect of mulch (97% reduction in ESP) is larger than the effect of being in a mesic Block (70% reduction in ESP). Subsoil ESP follows Na concentrations and the effect of site conditions is three times greater than treatments, conforming to the expectations of declining cations leaching intensity with depth depicted by the Ca/Na ratios.

Table B.11A. Na^+ and exchangeable sodium percentage in surface horizons.

Location	Treatment	Sample size	Na (mg L^{-1})			ESP (%)		
			mean	*min*	*max*	*mean*	*min*	*max*
Block 1	Mulch	7	8	3	14	8	3	14
	Unmodified	10	22	22	22	22	22	22
Block 45	Mulch	5	6	2	16	6	2	16
	Basin	2	7	5	8	7	5	8
	Unmodified	3	41	20	68	41	20	68
Block 6	Mulch	6	14	8	27	14	8	27
	Unmodified	3	270	36	739	270	36	739
Block 7	Mulch	4	394	23	1213	394	23	1213
	Unmodified	2	254	219	289	254	219	289
Block 812	Mulch	4	63	12	141	63	12	141
	Unmodified	2	33	12	53	33	12	53
Block 10	Mulch	4	24	7	45	24	7	45
	Unmodified	9	68	45	90	68	45	90

Table B.11B. Na^+ and exchangeable sodium percentage in subsoil horizons.

Location	Treatment	Sample size	Na (mg L^{-1})			ESP (%)		
			mean	*min*	*max*	*mean*	*min*	*max*
Block 1	Mulch	4	172	49	295	172	49	295
	Unmodified	4	578	31	1050	578	31	1050
Block 45	Mulch	4	81	9	196	81	9	196
	Basin	1	4			4		
	Unmodified	5	338	16	835	338	16	835
Block 6	Mulch	7	206	53	358	206	53	358
	Unmodified	6	562	179	947	562	179	947
Block 7	Mulch	5	835	218	2539	835	218	2539
	Unmodified	9	4350	851	9473	4350	851	9473
Block 812	Mulch	4	1784	1149	2945	1784	1149	2945
	Unmodified	5	576	25	2564	576	25	2564
Block 10	Mulch	5	1069	269	1541	1069	269	1541
	Unmodified	5	450	226	629	450	226	629

The combined effect of site factors and mulch treatment is tangible in the depth profiles of Ca/Na ratios for each block. In mesic blocks Ca/Na ratios below mulch remains higher than unmodified treatments in profiles at five of six Blocks (Figure B.15). Calculating the depth at which a smoothing spline fit to each profile intersects reveals that Ca/Na ratios remain higher in more mesic blocks to a depth of around 70 cm below surface (interquartile range 55-87 cm). A similar trend is observed in xeric Blocks, but the intersections is higher in the profile and the magnitude of difference is smaller (Figure B.10B). In more aridic Blocks Ca/Na ratios from mulched and unmodified treatments equilibrate at around 30 cm below surface (interquartile range 20-43 cm). Soil pH in the surface horizons of mulched treatments is slightly more acid than in unmodified profiles, a finding which is consistent in five of six Blocks (Mann-Whitney p-value 0.18). B horizon pH is virtually unchanged.

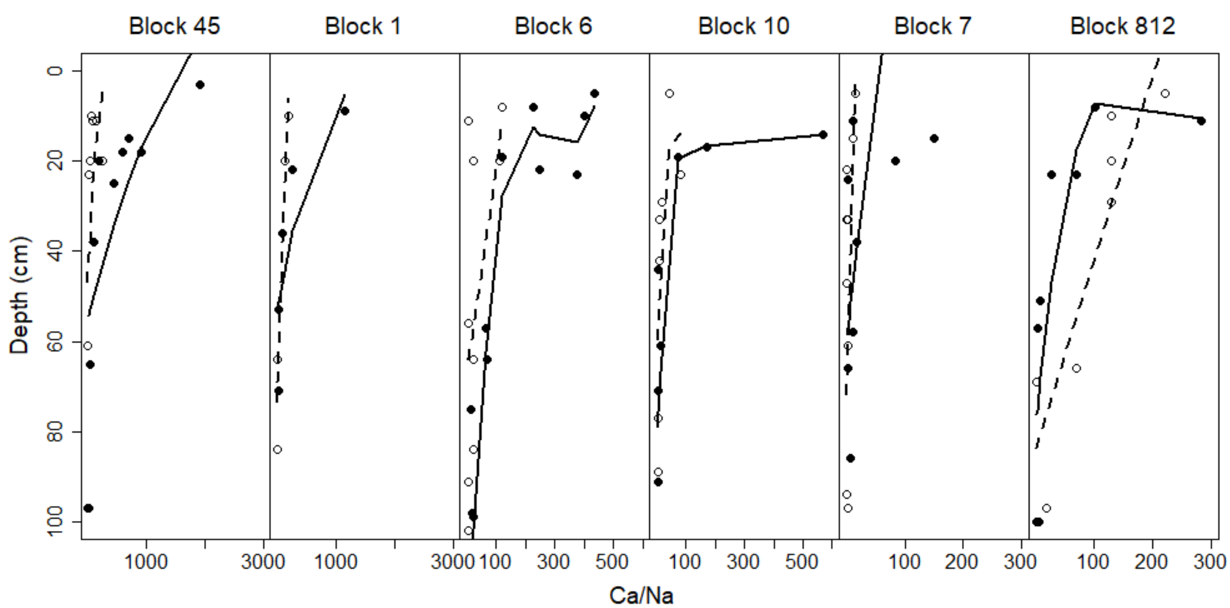

Figure B.15. Ca/Na ratio with depth for mulched (closed circles) and unmodified profiles (open circles). The smoothing spline shows the trend for mulched (solid line) and unmodified profiles (dashed line).

In mulched treatments total N and exchangeable K are weakly correlated (Kendal's tau = 0.38, p-value = 0.02), but uncorrelated in unmodified profiles (Kendal's tau = 0.27, p-value = 0.18). SOM is positively correlated with both N and K in mulched treatments (Kendal's tau = 0.45, p-value < 0.01 for both measures), but only with K in unmodified profiles (Kendal's tau = 0.66, p-value < 0.01) (Figure B.16). Exchangeable K concentration declines with increasing alkalinity in the surface horizons of both treatments, but the anticorrelation of K with pH is only significant in the unmodified group (Kendal's tau = -0.62, p-value = 0.03). SOM is uncorrelated with P_{av} in both treatments, and P_{av} is uncorrelated with other nutrients tested in this study.

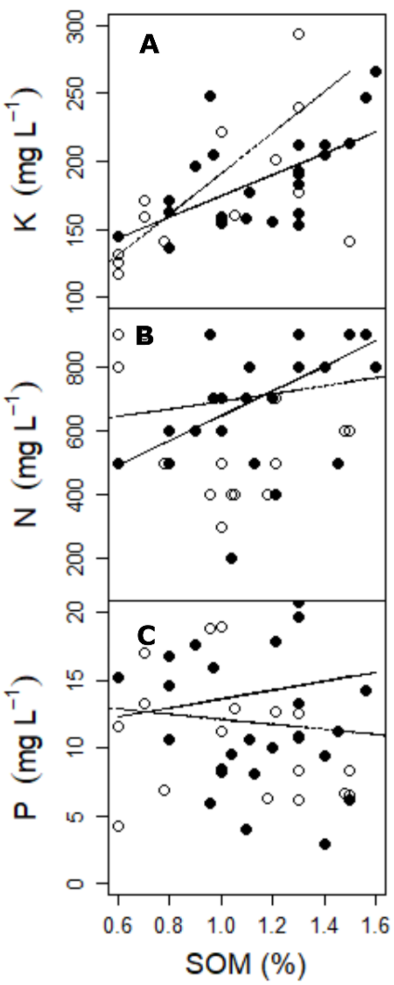

Figure B.16. Relationship between SOM and soil nutrients in mulched treatments (filled circles) and unmodified treatments (open circles). The least-squares fit line illustrates the strength of the correlation between SOM and nutrient concentrations in mulched treatments (solid line) and unmodified treatments (dashed line).

The sandy soils of the project area drain rapidly; measured bulk density, and reconstructed K_{sat}, are consistent with reference values for sandy loams (Clapp and Hornberger 1978) (Table B.9). Estimated wilting point and field capacity based on texture corresponds to the low water contents measured in profiles throughout the study area.

Table B.12. Soil parameters used in Eq. 1 for modeling soil water flux.

Parameter	*Value*
Average soil texture	Sandy loam
Bulk density (*BD*)	1.5
Saturated hydraulic conductivity (K_{sat})	24 (cm hr^{-1})
Field capacity (*FC*)	0.2 (g g^{-1})
Wilting point (*WP*)	0.08 (g g^{-1})

Direct precipitation from typical summer storms, with a 1-100-year recurrence interval (see Table B.1), would only generate modest downward water flux if fully infiltrated. Given soil parameters from Table B.12, Equation 1 estimates that a 1-5 cm water column would cease percolation within an hour above a depth of 24 cm (Figure B.17). Potential evapotranspiration, whether estimated by Equations 2 and 3, or derived from reference conditions (Allen et al. 1998), outpaces the average accumulation rate of direct precipitation as would be expected in an ustic moisture regime (see Table B.1). This is important because rewetting the profile by direct infiltration of summer precipitation would not extend the average depth of water penetration below the maximum achieved during winter months when evapotranspiration is negligible (Singh et al. 1998). Based on the modeled depth of water flux, observed change in Na^+ leaching intensity beneath an average mulched profile corresponds to a water column greater approaching 10 cm in height (Figure B.17). This amount of water could only be generated from storm runoff as 10 cm, even falling over a 30-day period, would constitute an extreme event in the historical record and is not reflective of average conditions.

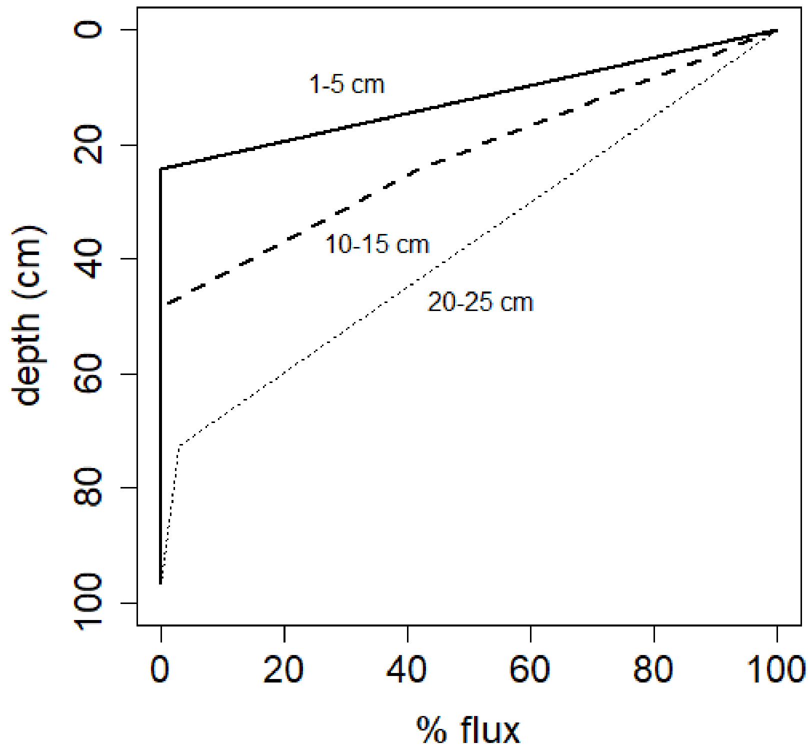

Figure B.17. Percent of a hypothetical irrigation input in flux down a soil profile (see Table B.9, Equation 1 in Methods and Material). The point at which water in flux reaches zero percent indicates the depth of water penetration for a given input.

Discussion and conclusions

Gravel mulch is not associated with significant declines in soil quality. The hypothesis that gravel mulch leads to a long-term disruption in organic matter cycling is not supported since no change significant reduction in SOM, C, N, P_{av}, of K^+ between mulch and unmodified treatments was observed. SOM in the fine soil fraction is unchanged in either surface or subsoil horizons in mulched treatments, and variability is SOM is driven mainly by site factors controlling water availability rather than the presence or absence gravel mulch. SOM reductions with cultivation have been found to correlate with P loss, despite increases in primary production, due to the removal of plant residue (Tiessen et al. 1983). In this study, mulch is associated with a consistent, modest, increase in P_{av}, and the change is of a similar magnitude as that associated with an increase in mesic vegetation, suggesting that mulch causes P_{av} enhancement via its positive effect on primary productivity. Available P measured in this study was uncorrelated to SOM and other plant nutrients, which contrasts with the finding that plant phosphorus uptake, SOM, N, are linked in natural soil experiments to increases in total P from plant residues (Boitt et al. 2018). One hypothesis to explain the decoupling of P_{av} and SOM under gravel mulch is that organic P is leaching from plant litter on the mulch surface and mineralized in the root zone rather than being incorporated as decaying organic matter. Organic P leaching has been demonstrated in agricultural soils receiving surface applied (unmixed) plant reside to the benefit of P_{av} (Sharpley and Smith 1989).

The nutrient and SOM content recorded in the basin feature in Block 45 is informative about the nature of run-off received by fields. Norton et al. (2007) reported that bare soil backslopes yield high concentrations of total P to run-off irrigated fields at Zuni. In the basin feature of Block 45, both SOM and P_{av} are enriched, indicating the deposition of run-off rich in organic colloids and macrobiotic crust (Norton et al. 2007). P_{av} is enriched in the A horizon of mulched fields in Block 45 when mulch is *included* in the measurements, a unique observation in the data, suggesting that in some geomorphic positions mulch may trap nutrient rich sediment.

Previous soil studies reporting base nutrients in precontact agricultural fields elsewhere in the Southwest found no change in Ca^{2+}, Mg^{2+}, and K^{+} between rock alignments and unmodified soil profiles (Sullivan 2000). Other studies show declines in base nutrients beneath volcanic cinder mulched fields compared to uncultivated areas, but the authors of these studies do not interpret the declines as a significant reduction in fertility (Berlin et al. 1977; Edwards 2007), and the small sample size limits interpretation. The results of this study show modest but consistent declines in CEC in gravel mulch profiles across study Blocks, which is associated with losses of Mg^{2+} and Na^{+}. Other based nutrients are unchanged between treatments.

Studies on the changes in sodium concentrations induced by recent land use and cultivation show that Na^{+}, being readily mobile, can reflect processes on the scale of 10-100 years (Chabbra 1996). This suggests that the observed changes in Na^{+} leaching intensity beneath gravel mulch is the result of processes which may have changed since the time of cultivation. In general, fields are not affected by exchangeable sodium buildup, but some soils, particularly in more xeric sites, have ESP levels high enough to induce yield declines in maize, and perhaps even cotton. Maize and cotton are moderately tolerant of saline conditions, with roughly 50 percent yield reductions occurring at ESP levels of 35 and 50 respectively (Bajwa et al. 1983; Longenecker 1974; Pearson 1960;). Maximum ESP values in surface horizons of unmodified treatments in Block 6 (a more mesic site) and mulched treatments in Block 7 (a more xeric site) are around 20. Unmodified and gravel mulch treatment subsoil in Blocks 7, 812, and 10 (all drier sites) have maximum ESP values between 20 and 60. These levels suggest the potential for problematic sodicity, particularly for maize production, in the run-off irrigated soils in the study area, but is not direct evidence that crops growing in mulched fields were actually impacted. Given that the average ESP across treatments and Blocks is less than 5, deleterious sodicity should be considered an isolated risk, perhaps slightly reduced by mulch, rather than a significant problem facing Puebloan farmers at Poshu'Owingeh.

The 40th percentile particle size in the A horizon is significantly increased by the application gravel mulch (0.77 mm from 0.16 mm). This corresponds to a large increase in modeled infiltration rate compared to unmodified surfaces. This is consistent with hydrological models of gravel mulch fields which project that any realistic storm intensity could have been completely intercepted and infiltrated by a mulched surface including the additional flow from run-off sources from catchments ranging in size from ca. 100-1000 m^2 (Dominguez 2000:168, 215). However, over time gravel has been incorporated into the A horizons of mulched fields and now most clasts are well embedded in the soil surface. This probably significantly reduces the real difference in infiltration rates between an old mulch surface – with embedded clasts – and bare soil (Poesen et al. 1990). Increased vegetation density in gravel mulched fields probably helps reduce runoff rates from mulched fields compared to unmodified soils since vegetation has a positive ecohydrological feedback for the stability of soils and water conservation (Wilcox et al. 2003).

Mulch does not significantly increase soil water capacity or the ability of soils to retain moisture in drying conditions. Measured field water content of the soil fine fraction is identically distributed between treatments with all variability driven by site factors. Soils in the study area are well drained and the water content varies with site factors. Sites with qualities indicative of higher available moisture had on average 64 percent more soil water than more aridic sites. Median water content, irrespective of treatment, for the entire root zone was near the witling point for loamy soils (Rendig and Taylor 1989). This contrasts with an oft-cited function of gravel or lithic mulch: namely its utility in increasing soil water retention (for example Stevenson et al. 1999). Mulch does decrease evaporation for the surface soil layer which results in a slight increase in plant water availability (Dominguez 2000), but during the growing season transpiration far outpaces evaporation and plants can extract water far deeper than mulch can affect. Some confusion may lie in the interpretation of experiments in which gravel mulch plots are hand watered to make up soil water deficits from plant water consumption thus giving the impression that mulch increases water availability (White et al 1997). Increases in natural plant density and vigor observed in this study and elsewhere (see Periman 1995) are probably a result of small differences in early season soil moisture – caused by reduced evaporation – and large differences in the amount of water received by mulched profiles during the growing season. The latter factor is the only mechanism which can account for the fact that plants have more available water, despite higher consumption rates and identical hydrologic properties, and observed changes in leaching intensity resulting from deeper water penetration.

There is no major difference in the hydrologic properties of the soils analyzed in this study but an important pattern in the depth of Na^+ leaching indicates changes in water balance associated with gravel mulch fields. The depth profiles of Ca^{2+}/Na^+ show that leaching intensity is increased in the upper 30-70 cm of gravel mulch profiles in all but the driest locations. Because the texture and gravimetric water content of the subsoils are identical between treatments at each study Block, the inferred change in water flux is unlikely to be due to differences in hydraulic conductivity, but rather to greater levels of water flux. Dissolved ions enter the soil with runoff and are removed via drainage and plant uptake while ions precipitate via evaporation. With irrigation, ion loss through leaching tends to predominate in most situations and cation leaching is positively related to irrigation water input (Pratt 1978; Qadir et al. 2003). Importantly, the depth of Na^+ leaching should indicate the average depth of water penetration (Chadwick and Chorover 2001).

Soil pH is slightly more acidic (-3%) in mulched treatments compared to unmodified treatments in mesic Blocks, but across all Blocks the difference is negligible. Examining Figure B.11 shows surface horizons are slightly more acidic under mulch and subsoil horizons are slightly more alkaline under gravel mulch treatments. The loss of cations from soil causes acidification and the accumulation of positively changed ions results in the opposite effect (van Breeman et al. 1984). The fact that cation leaching is confined mostly to Na^{2+} in this study – the smallest proportion of total exchangeable bases – could explain why soil pH follows expectations for a leaching profile but only to a degree proportional to the small total change in total base counting ions.

Based on generalizations about soil attributes and the local climate, direct infiltration of rain and snow is unlikely to have caused the change in the depth of Na^{+} leaching. A storm bringing 5 cm of precipitation in 24 hours to the study area has a recurrence interval of roughly 25 years, and 10 cm of rain in 24-hour period would be an extreme event beyond the 1,000-year recurrence interval (Perica et al. 2019). The increase in the depth of average depth of water penetration beneath mulch is most likely caused by increased runoff delivery compared to unmodified locations. Reconstructing precise runoff potentials for each study Block is beyond the scope of this project, but it is possible to speculate on the processes generating runoff across the study area based on general information about variability in the depth of water flux and the agricultural landscape around Poshu'Owingeh.

Two processes could be responsible for runoff delivery to gravel mulch fields: overland flow in excess of infiltration (Hortonian flow) and saturated surface flow along partial paths. In situations with heterogenous land use histories and substrates, surface flow can be generated by numerous means; runoff form low permeability rocky slopes, runoff from dense patches of leaf litter, runoff due to changes in soils texture caused by cultivation (Nicolau et al. 1996). Hortonian overland flow should decrease with hillslope length at small scales (10-100 m^2) (Bergkamp 1998; Lal 1983; Stomph et al. 2002). Connected surface flow may become important to total runoff volume in dry soils with thin A horizons during intense rainfall events (Gomi et al. 2008). Natural pathways for connected surface flow are rills and hillslope channels, erosive features whose length scales with increasing runoff generation and soil loss (Rejman and Brodowski 2005). Hillslopes characterized by highly permeable soils and low rainfall amounts experience overland flow along partial pathways where locally saturated conditions occur (Dunne and Black 1970). Connected surface flow volume scales with hillslope length and could be a particularly important component of runoff contribution in humanly modified landscapes (Gilley et al. 1987).

Evidence from field excavations, historical research, and surveys suggest that Puebloan farmers increased the scale and connectivity of surface flow paths, by digging ditches, and created impermeable barriers (rock alignments) which could have contributed to microtopographic saturated flow paths in strategic landscape positions. Such an engineered hillslope would be dominated by non-Hortonian processes and total runoff volume should increase with hillslope length. In other locations, rocky slopes with lower infiltration capacity would have needed minimal modification to generate runoff. It should also be remembered that some study Blocks (812) do not exhibit increased Na^+ leaching intensity indicating that some fields no longer or never received significant runoff, suggesting diversity in field construction and use.

Previous geoarchaeological studies in the Northern Rio Grande have documented evidence for runoff irrigation and suggest the outlines of a system of water control in which gravel mulch was one aspect (Camilli and Banet 2012). Direct evidence of runoff irrigation includes: (1) deposition of slope wash over features, (2) alternation of alluvial depositional facies (sand – coarse channel fill) indicating active channel change, (3) presence of shallow ditches with head gates parallel to some mulched fields, and (5) the erosion of mulched fields by channel incision. Hypothetically, this system may have operated by intercepting ephemeral overland flow along hillslope segments and converting it to saturated flow along rock alignments which directed it into a ditch or rill running parallel to a gravel mulch field border and turned out in fields at intervals. At Poshu'Owingeh, diversity in the configuration of surface flow paths in relation to gravel mulch fields in different topographic settings supports the hypothesis that different mechanisms are responsible for delivering runoff to fields (Figure B.6 and B.7), but a more detailed analysis is beyond the scope of this study. Other features suggest a diversity of active run-off management as well. The morphology, construction, sedimentology, and soil chemistry of the basin feature in Block 45 provides evidence for water diversion, and possibly impoundment (Figure B.8) while channel check dams were used to control channel flows (Figure B.9).

Based on its phenology, cotton is well suited to mulch agriculture in the northern New Mexico climate regime. The effective rooting depths of cotton and maize are dynamic, but cotton seems particularly well suited to cultivation in mulched fields. Cotton has an effective rooting depth of around 90 cm below surface, but extents rootlets to a depth of to nearly 2 m below surface (Kepler et al. 1973; Taylor and Kepler 1971; Wang et al 2010). Maize has an effective rooting depth of around 45 cm but extends a taproot down to depths to more than 2.5 m below surface (; Panda et al. 2004; Sharp and Davies 1986). Interestingly, in experiments with isotopically labeled water, maize was observed to extract shallow water sources (< 50 cm) throughout the growing season whereas cotton progressively extends the depth of water uptake from 0-20 cm in seedling stage, to 90 cm in bloom, to greater than >90 cm below surface during boll opening (Wang et al. 2009).

Pollen evidence from gravel mulch at Poshu'Owingeh and elsewhere in the Northern Rio Grande suggest that cotton was the primary crop grown in gravel mulch (Appendix C; Camilli et al. 2019). The most crucial time for water supply in the life cycle of a cotton plant is during the development of floral buds prior to first flowering (Wrona et al. 1999). If cotton was planted in late April or the beginning of May, first flower would occur soon after the middle of June, or at the beginning of monsoon season in the northern New Mexico. Based on daily weather records (Prism Climate Data Group 2019) the largest magnitude 24-hour rainfall events typically occur in the last half of June through early July. This fact suggests that the reconstructed irrigation mechanism of gravel mulch is particularly suited to the lifecycle of cotton, which would require irrigation at precisely the time of monsoon arrival.

Based on the estimated water flux associated with the observed change in Na^+ leaching intensity gravel mulch profiles receive an irrigation pulse roughly equivalent to a 10 cm water column. However, 10 cm of precipitation, even falling over a month, would constitute an extreme event, and is therefore not reflective of average conditions. Furthermore, direct precipitation would probably affect both treatments equally as the infiltration benefits of mulch are likely reduced by partial burial of clasts. Higher levels of water flux beneath gravel mulch must be due in no small part to their landscape positions and possible lingering effects of landscape modifications designed to enhance connected saturated flow. This suggests that gravel mulch in Rio Chama functioned to increase infiltration of storm runoff in most locations, prevent erosion from channeled runoff, and decrease evaporation to conserve early season soil moisture.

Paleo-proxies for summer precipitation suggest that past climate could have been more suitable for this hypothetical cotton-mulch complex, and the timing of the expansion of agricultural villages through the Rio Chama Basin coincides with optimal conditions (Figure

B.18). Puebloan style cotton weaving technology is believed to have diffused into the Northern Rio Grande in the early stages of the period characterized by rapid population increases (Peckham 1984). Population growth in the Rio Chama Basin followed growth elsewhere in the region and is coincident with the spatial expansion of farming villages (Appendix A). Direct dates for gravel mulch fields are rare, but the small body of evidence suggests that gravel mulch expanded along with newly founded settlements beginning in 14th century A.D., or at the very earliest, the late 13th century (Camilli et al. 2019; Moore 2009).

This was simultaneous with an increase in summer precipitation in the Rio Chama Basin (Towner and Salzer 2013), which probably reflects strengthening of the North American Monsoon (NAM). Late-wood tree-ring width reconstructions from western New Mexico suggest the onset of pluvial conditions characterized by more summer precipitation and perhaps an earlier onset of the monsoon began in the final decades of the 13th century A.D. through the late 14th century (Stahle et al. 2009). Farther south, in Mexico, a lake record for peak contributing runoff area, controlled by the intensity of the summer storms, shows that the NAM strengthened during the 13th and 14th centuries A.D. (Metcalf 2010). These conditions changed significantly by the middle 15th century. The NAM weakened through the 15th century and generally lower levels of summer precipitation and drought are recorded in the tree-ring widths in the Rio Chama Basin in the middle 15th century. This presents a striking correspondence between the phenology of cotton, climate, and agricultural technology.

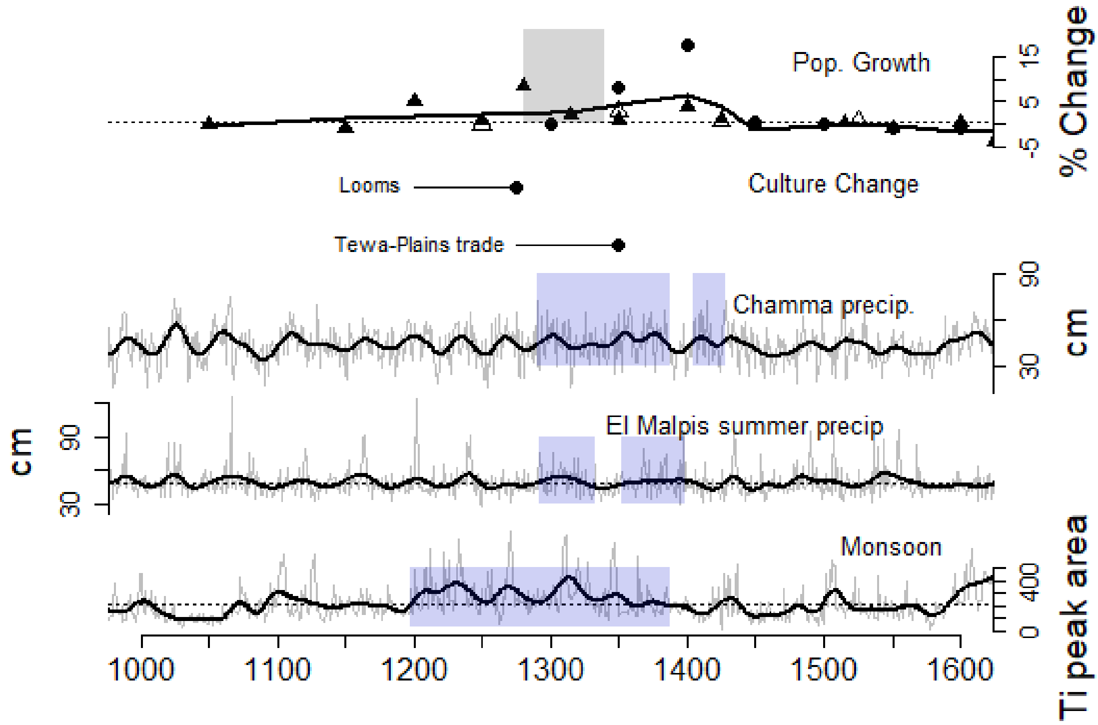

Figure B.18. A composite reconstruction of population growth in the Chama Basin (top) (Eiselt 2019; Maxwell 1994; Ortman 2012) followed the period of rapid spatial expansion in the area (top, shaded region) (Appendix A). Puebloan style looms – and perhaps cotton – diffused into the area immediately prior to Chama population expansion (Peckham 1984), and evidence for Plains-Pueblo exchange is manifest around this time as well (Crabb 1968; Lentz 1993) (second from top). Precipitation in the Chama Basin is summer dominant and the tree-ring reconstruction by Towner and Salzer (2013) (third from top) corresponds with July precipitation reconstructed in western New Mexico (fourth from bottom) (Stahle et al. 2009). Stahle (2009: Figure B.11) interprets the late 13th through 14th century pluvial (blue shaded regions) as resulting from a low frequency of winter drought conditions combined with more intense, and occasionally early onset, of Monsoon precipitation. A lake sediment record of titanium (Ti) from Jalisco, Mexico provides a record for the peak contributing area of runoff and is a proxy for precipitation, >80 percent of which comes from the summer monsoon (bottom) (Metcalfe et al. 2010). This record indicates a persistent increase in monsoonal precipitation from the 13th through 14th centuries A.D.

The irrigation mechanism inferred for gravel mulch and the life cycle of cotton seems ideally suited for the 14th century climate in the Rio Chama and corresponds to the rapid population expansion in this area. This supports a hypothesis that cotton played an important role in the rapid socioeconomic growth of the region. It also suggests that technological development during changing climatic conditions promoted the development of the cotton-based component of this economy. The timing of these changes suggests that people responded rapidly to changes in climatic conditions which created opportunities for economic and demographic expansion. The available data show that, along with settlement changes, new technologies were developed rapidly to create niches favorable to high value agricultural products that facilitated participation in exchange networks and may have contributed to the overall economic security of individuals and groups in the Chama Basin.

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APPENDIX C: NEW POLLEN EVIDENCE FOR INTENSIFIED COTTON PRODUCTION IN NORTHERN NEW MEXICO AFTER A.D. 1350

Introduction

Interest in cotton agriculture in the Northern Rio Grande (NRG) stems from a desire to understand the development of what appears to be a regional economy connecting people across the region by the time of European contact. In one model, the development of interpueblo exchange and resource redistribution is hypothesized to have emerged as an adaptation to subsistence risk and population pressure on resources, with schedules ceremonial events serving to redistribute resources across communities (Ford 1968; 1972). Snow (1981; 1991) elaborated this model to propose that mutualistic networks and diverse cropping strategies would have developed to counter the environmental risks specific to maize agriculture. Spielmann (1983) hypothesized that a significant, if not predominant, node of a regional Puebloan exchange network involved Plains Villagers and Apachean groups in the exchange of bison products for maize, ceramics, obsidian, and turquoise. This argument relies heavily on documented relations between Plains and Pueblo groups and the archaeological record for Plains goods in Puebloan contexts and vice versa (Spielmann 1991). Hill (1998) questioned the details of this model based on the lack of empirical evidence for maize surplus production and speculation on the function of ubiquitous dryland agricultural features. Rather than maize it was hypothesized that – for the Eastern Pueblos south of present-day Santa Fe – runoff irrigated cotton production underwrote hypothetical inter and intracommunity exchange (Herhahn and Hill 1998). More recently cotton has been hypothesized to have played an important role in exchange-based, regional interaction networks, that contributed to non-linear growth in the scale of NRG society and economy (Ortman and Coffey 2019; Ortman and Davis 2019).

Evidence suggests that specialized cotton growing technology emerged during the period of rapid population expansion in the NRG and was particularly important among the northern Tewa villages that grew rapidly after A.D. 1350 (Camilli et al. 2019). This technology – gravel mulch and related runoff irrigation infrastructure – represents a constructed cotton niche which functioned by conserving antecedent soil moisture and enhancing total water flux by capturing storm runoff (Appendix B). Connecting the emergence of an ecosystem engineering technology, specialized crop production, an increased socioeconomic complexity is a significant discovery because it provides an empirical example of how niche construction activity and innovation relate to the historical development of social complexity in food producing societies. This problem is highlighted by recent studies on role of population size, connectivity, and environmental risk in the development of cultural complexity and technological diversification (Collard et al. 2013; Fogarty and Creazan 2017).

Cotton textiles, and possibly cotton fields, were observed by Spaniards in the NRG in the middle to late 16th century A.D. (Bolton 1908; Hammond and Rey 1928; 1929). However, a review by Brenneman (1995) reminds researchers that these early documents make few verifiable, first person, observations for cotton cultivation, its extent, or importance. It is, therefore, necessary that archaeologists find direct and indirect evidence for cotton cultivation and reconstruct its importance to the development of regional scale economies. Furthermore, recent summaries of perishables research in the desert regions of western North America make it clear that knowledge of textile consumption and manufacture far outpaces evidence of fiber production and agriculture (Leach 2018). Even in areas with abundant evidence for spinning and weaving, such as the western Mesa Verde region, direct evidence for cotton cultivation is lacking (Crabtree and Bellorado 2016).

Cotton textile production is closely associated with trends in the development of social complexity and population aggregation in the Puebloan Southwest. Evidence for the spinning and weaving of cotton textiles is largely found in contexts postdating A.D. 1150 (Kent 1957 Webster 2006). Based on a synthesis of the occurrence of loom anchors in kivas throughout the NRG, Peckham (1984) proposed that cotton was introduced to this region between A.D. 1200 and A.D. 1350. Direct evidence for cotton agriculture in the NRG has been accumulating since Dean (1995) reported cotton pollen associated with gravel mulched fields in the Rio Chama Basin. Recent archaeological investigations into indigenous water management technology in the NRG have recovered cotton pollen in direct association with a variety of runoff irrigated fields (Camilli et al. 2019). Cotton pollen has been found in fields dating to A.D. 1500-1700 at the mouth of the Rio Chama and Rio Tesuque, and from fields dating to A.D.1350-1550 in the lower Rio Chama, the Ojo Caliente, and the Rio del Oso valleys (Dean 1995; Moore 2009; Smith 2008; Smith 2012) (Figure C.1). In general, cotton tends to predominate over maize in mulched fields, and, based on the rough chronology of the extant data, cotton agriculture increased in prevalence from ca. A.D 1350 to the contact period (Smith 2012).

These findings lend support to the hypothesis that cotton underwrote a high degree of economic connection between communities within and outside the NRG. However, not all studies report high cotton-to-maize ratios in mulched fields (Holloway 2009), and the small number of pollen studies leaves considerable uncertainty about the density of cotton agriculture across space and time. It is with these facts in mind that this paper reports pollen evidence for the frequency and abundance of cotton and maize in gravel mulched fields associated with the

Ancestral Tewa pueblo of Poshu'Owingeh (LA 274), and observes change in vegetation communities that correspond to local population history. The results are compared to another well documented complex of agricultural features at Yunge Hills associated with Yunge'Owingeh (LA 59/60) near present day Ohkay'Owngeh.

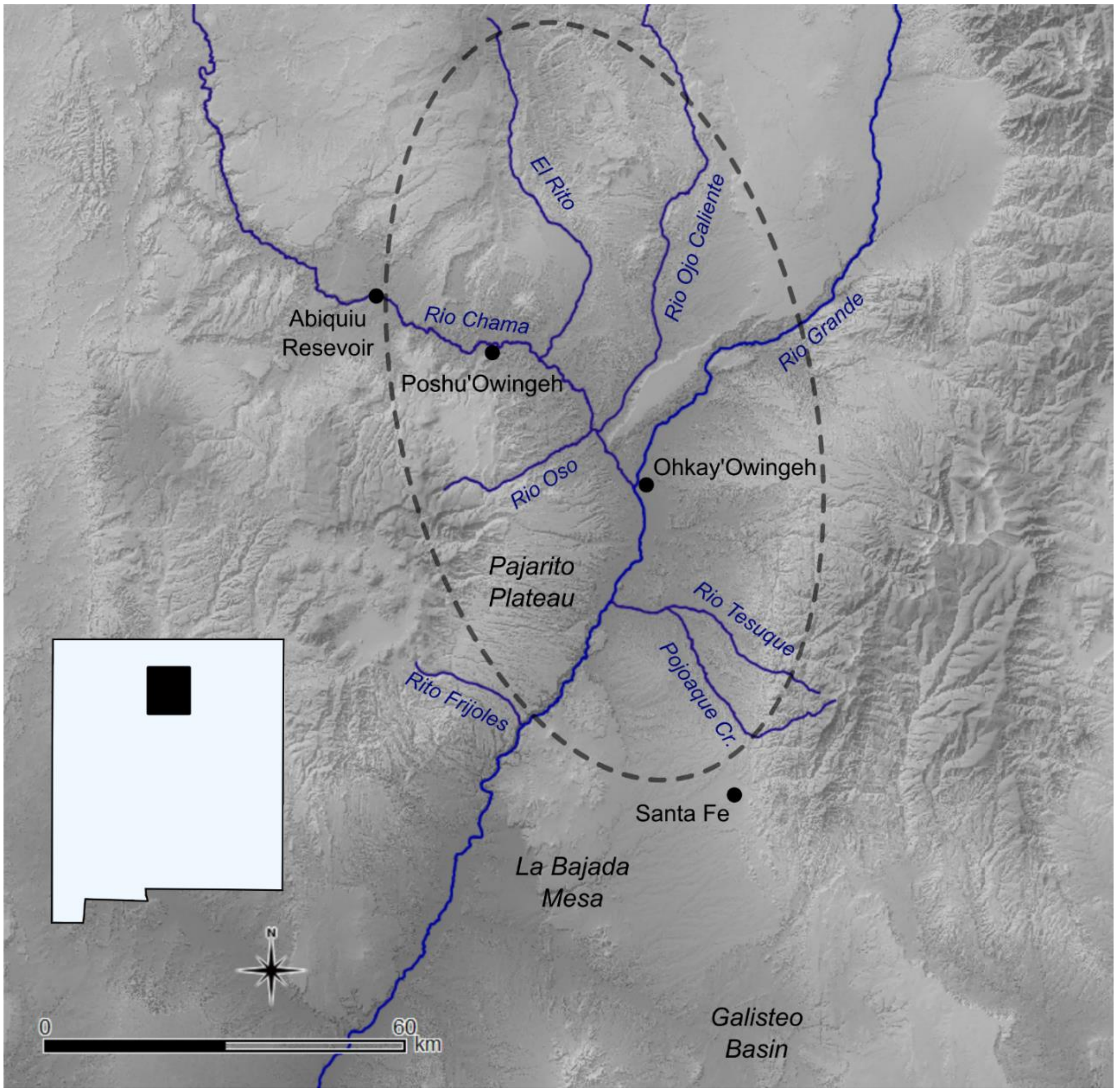

Figure C.1. Map showing the location of the study area and places discussed in the text.

Methods and material

The goal of pollen sampling and analysis at Poshu'Owingeh for this project was to document the plant community associated with the Poshu'Owingeh agroecosystem and recover direct evidence for the types of domesticates and cultivated or encouraged wild taxa grown directly on gravel mulch fields. Sampling and analysis were conducted with the assistance of Susan Smith, Chris Banet, and Kurt Anschuetz who have conducted similar work at other runoff irrigated farming localities in the Northern Rio Grande. This ensured comparability with a particularly well-documented gravel mulch complex at Yunge Hills, near Ohkay'Owingeh Pueblo (Camilli et al. 2019) (Figure C.1). Continuity in field and laboratory methods allows an inference about nature of agricultural change from late precontact (ca. A.D.1400-1550) to early colonial (ca. A.D. 1550-1700) contexts.

Study site

Twelve agricultural features were sampled for pollen analysis southeast of room blocks at Poshu'Owingeh (Figure C.2). Poshu'Owingeh is a major Ancestral Tewa village situated south of the Rio Chama, and is believed to have had more than 1,100 rooms, for a maximum potential population of around 3,000 individuals (Duwe et al. 2016), although the actual population may have been much lower at any given time (Anschuetz 2007). The first farming settlements in the immediate vicinity probably consisted of a number of smaller dispersed room blocks that ceased to be occupied as early as the late 14th century (Beal 1984; Fowles 2004). Based on the architectural layout of Poshu'Owingeh compared to similar villages in the Chama Basin, Poshu'Owingeh may have experienced rapid growth early in its history from the wholesale incorporation of a nonlocal community (Duwe 2011). Tree-ring dates indicate room block construction after A.D. 1350 with major construction around A.D. 1420 (Robinson and Warren 1971).

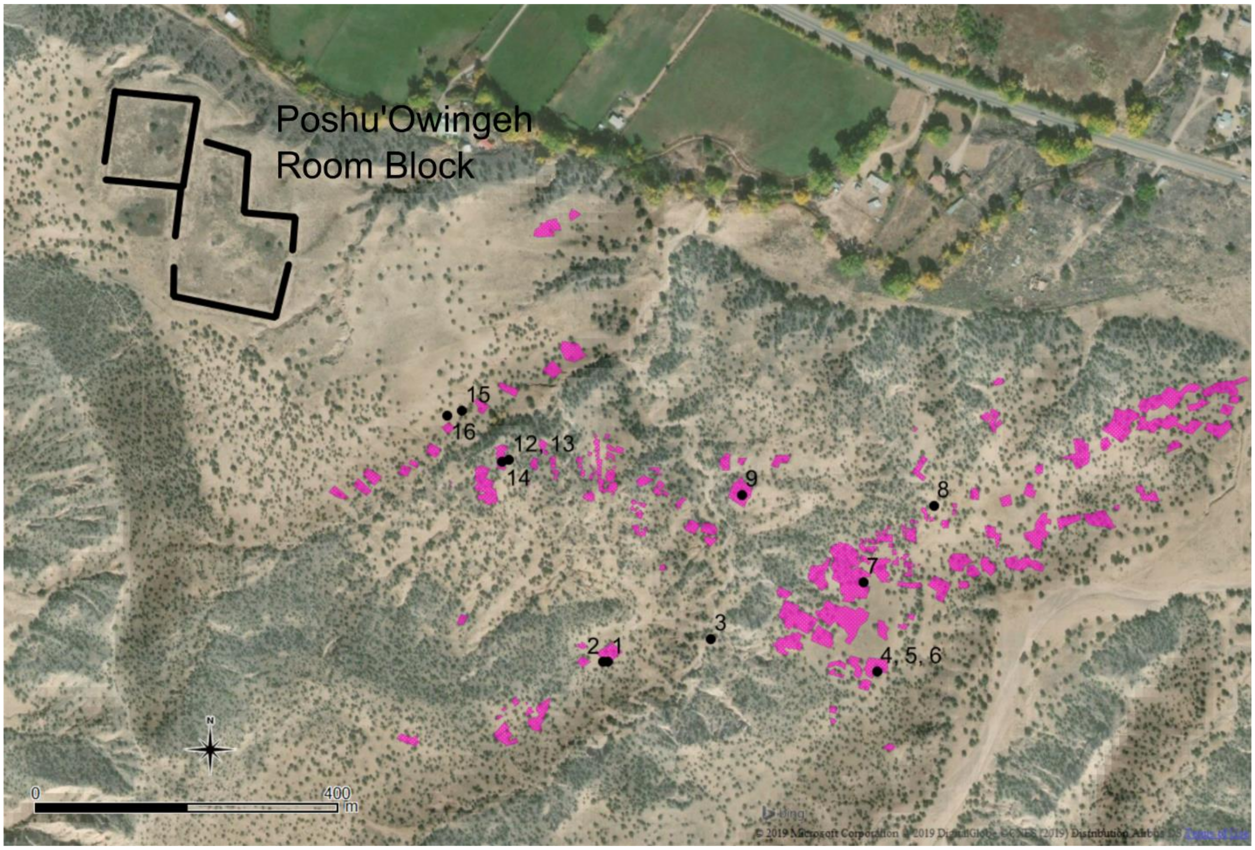

Figure C.2. Extent of gravel mulched fields (total 3.9 ha) (magenta polygons) around the Poshu'Owingeh room blocks (thick black lines) and the locations of pollen sample (n= 16). The numbers correspond to the pollen sample ID number.

Gravel mulch fields at the site are situated at an elevation from 1835 m to 1870 m amsl. Climate is classified as a cold, semi-arid steppe (Peel et al. 2007). The climate lacks a true dry season, though roughly half of the average annual precipitation of 276 mm occurs during the summer. Mean annual temperature is 11°C, with the warmest summer month (July) averaging 23°C and the coldest month (January) averaging 0°C. Growing season (May-Sept) averages 19.1 °C while the average minimum temperature climbs above freezing in April and exceeds 5°C in May suggesting that crops may have been planted in latest April through May to avoid early season frost. For cotton, requiring a minimum of 80-100 days prior to harvesting mature (if not completely open) bolls (Lewton 1912), this places harvest no earlier than the first week of July, although August seems more likely based on the timing of the monsoon which begins in the middle of June and would have provided important soil moisture during plant development.

Field sampling

Soil samples were collected from shallowly buried contexts in agricultural features to quantify the fossil plant taxa associated with the runoff irrigation features at the site. In profile, gravel mulch is differentiated from the natural surface by a 5-15 cm thick surface soil horizon of uniform coarse fragments in a sand matrix (termed the A1 horizon). The A1 horizon overlies, and is mixed with, the natural A horizon (A2) which contains a lower density of coarse fragments (Appendix B; Camilli et al. 2019). Both the A1 and A2 horizons contain fossil pollen from cultivars. Approximately 30 g of bulk soil were collected from each context listed below and placed in sterile plastic bags. Surface control samples were collected to quantify the pollen spectrum of the present study area, and to gauge the level of taphonomic degradation from agricultural levels.

Pollen samples were collected from five categorical contexts in the agricultural fields around Poshu'Owingeh: (1) the modern surface soil (n = 2), (2) slope deposits which stratigraphically overlie an agricultural surface but are below the modern surface (n = 2), (3) agricultural soil layers in non-mulch features (n = 2), (4) directly from lithic mulch (n = 4), and (5) agricultural soil layers directly beneath gravel mulch (n = 6) (Table C.1). The working hypothesis guiding field work was that modern surface samples are representative of the contemporary vegetation community; the second category represents the historic vegetation community that postdates the agricultural occupation of the site; non-mulch agricultural layers represents the general vegetation community during the agricultural occupation; samples from mulch represents the pollen rain directly on gravel mulched surfaces during and after their use; and sub-mulch samples are a mixture of fossil pollen from before mulch construction and during mulch use.

Laboratory methods

Susan Smith conducted standard and intensive scanning microscopy (ISM), and prepared a descriptive report detailing the results and methods employed (Supplement 1). Chemical extraction was performed at Texas A&M Palynology Laboratory by the following protocols: soil carbonate and silicate removal by hydrochloric and hydrofluoric acid treatments, followed by heavy liquid flotation (zinc bromide) to separate pollen from mineral and organic soil. Samples were spiked with a *Lycopodium* tracer (20,848 spores) before processing to statistically estimate pollen concentration.

For standard microscopy, pollen grains were counted and identified from standard references (Fægri et al. 1989; Kapp et al. 2000; Moore et al. 1991) to a sum ≥200 on a Microstar compound microscope at 400x magnification. Pollen aggregates were counted as one grain per occurrence and recorded separately. Grass family (*poaceae*) pollen was divided into three taxa (Fægri et al. 1989:284-286): maize pollen (>60 µm diameter with large ringed pore), large diameter *poaceae* (30-60 µm), and general *poaceae* (<30 µm). Pine (*pinaceae*) grains were separated by size into two categories that map the predominant pines of the Southern Rocky Mountain ecosystem: ponderosa (*Pinus ponderosa*) (>70 µm) and Colorado pinyon (*Pinus edulis*) (<70 µm) (Jacobs 1985).

ISM differs from standard microscopy in that rather than ceasing analysis of a sample after 200 pollen grains are counted, ISM involves scanning at 100x until the number of tracer grains encountered is proportional to an appropriate target concentration (Dean 1995; Dean et al.1998). The working assumption is that any pollen taxa identifiable at 100x magnification occurring at equal or greater density than the target concentration will be observed in successive scans. The target concentration for ISM in this project is 1.0 gr g^{-1}, comparable to maize concentrations documented in previous studies in the region (Smith 2008: Table 63.11). The advantage of ISM is that it provides a statistical threshold for the reliable identification of cultigens and encouraged wild plants that are typically found in fossil pollen assemblages at low concentrations. Such taxa in Southwestern archaeobotanical assemblages could include squash, cotton, maize, agave, and cacti.

I present pollen counts in this report and summarize these counts by context as percentages, absolute pollen taxa concentrations, relative concentrations, and ubiquity. Pollen concentration (gr g^{-1}) is a measure of pollen taxon density and is calculated as:

$$\frac{pollen\ sum / tracer\ count}{initial\ tracer\ spike} * \frac{1}{sample\ weight\ (g)} \qquad (1)$$

The relative concentration indicates the density of pollen within a particular context relative to the overall pollen concentration recovered from that context. This measure provides a way to compare pollen taxa concentrations across contexts with different preservation levels, and therefore, different pollen concentrations. Ubiquity quantifies the percentage of samples in which a pollen taxa or group of taxa are present.

Table C.1. Summary of pollen sample attributes.

Sample	Context	Soil Horizon	Depth (cm)	Pollen sum	Tracer sum	Degraded sum	Concentration (gr g^{-1})	Taxon richness
1	Upper mulch	A1	1-16	204	79	23	5383.5	12
2	Non-mulch agricultural (rock alignment)	A	11-13	311	39	42	16624.9	14
3	Lower mulch	A2	11-15	208	86	30	5042.3	12
4	Non-mulch agricultural (basin)	Bw	29-34	263	38	40	14429.0	13
5	Post-agricultural (basin)	Bw	22-29	261	43	32	12654.3	11
6	Post-agricultural (basin)	AB	16-21	328	39	31	17533.7	8
7	Lower mulch	A2	9-13	201	73	23	5740.3	14
8	Lower mulch	A2	10-13	291	51	31	11895.6	11
9	Lower mulch	A2	9-14	200	201	26	2074.4	14
10	Modern surface	A	0-2	493	40	13	25695.2	16
11	Modern surface	A	0-2	419	58	21	15060.9	15
12	Lower mulch	A2	12-17	114	161	18	1476.2	10
13	Upper mulch	A1	0-12	355	74	19	10001.4	15
14	Upper mulch	A1	0-13	304	49	16	12934.3	14
15	Lower mulch	A2	7-11	204	76	28	5596.0	16
16	Upper mulch	A1	0-13	227	165	35	2868.2	15

Results

Field study at Poshu'Owingeh characterized the contemporary vegetation community at the site and collected 16 pollen samples from agricultural and unmodified contexts to evaluate the function of fields and infer changes in the vegetation community. Analysis identified cultivar pollen, native taxa, and recently introduced non-native plant taxa. Agricultural soil layers are associated with higher levels of disturbance taxa while the modern surface is dominated by arboreal pollen. Both maize and cotton were recovered in pollen samples. Cotton predominates and was found directly associated with gravel mulch and in non-mulch agricultural contexts.

Standing vegetation

The contemporary vegetation near Poshu'Owingeh is characteristic of the juniper savanna type of Southern Rocky Mountain pinyon-juniper ecosystem (*Pinus edulis* and *Juniperus monosperma*) (Jacobs 2008). Grass (*Poaceae*) represents ≈ 40 percent of the ground cover across the area. Galleta (*Hilaria jamesii*) is most common with buffalo grass (*Bouteloua dactyloides*) and blue gramma (*B. gracillis*) thriving on gravel mulch. Dropseed (*Sporobolus spp.*), three-awn (*Aristida spp.*), and little bluestem (*Schizachyrium scoparium*) are also present. One-seed juniper (*J. monosperma*) comprises ≈ 30 percent of ground cover with occasional Colorado pinyon (*P. edulis*) present. Nearly all pinyons observed in the study area are dead, with very young (probably post-dating 2001) pinyons growing under juniper nurse trees. Pinyon are more frequent in steep rocky terrain outside of the field areas. Cottonwood (*Populus fremontii*) are sparsely distributed along water courses, growing directly in the sandy ephemeral channels of small v-shaped valleys and canyons and along the floodplains of wider bottomlands. Prickly pear (*Platyopuntia spp.*), rabbitbrush (*Chysothammus spp.*) and snakeweed (*Gutierrezia sarothrea*) are abundant, as is cholla (*Cylindropuntia spp.*) near the Poshu'Owingeh room blocks. Saltbush (*Artiplex spp.*) and yucca (*Yucca spp.*) are present but rare.

Poshu'Owingeh pollen results

Thirty separate pollen taxa were identified in the 16 samples from the various contexts around Poshu'Owingeh (Table C.2). Complete pollen counts for all taxa in each sample are provided in Supplement 2. Seven plant functional categories are discussed in this section along with the pollen concentrations for cultigens identified in ISM analysis (Table C.3 and C.4).

Fossil pollen was generally well preserved in agricultural soil layers. All samples, except Sample 12, yielded pollen grain counts >200 by standard microscopy, and the percentage of degraded grains are well below 50 percent in all samples, a heuristic level for good pollen preservation from archaeological contexts (Bryant and Hall 1993). Exotic taxa (historically introduced) were relatively rare in the Poshu'Owingeh samples. Pecan/hickory and Russian Olive were recorded in the surface controls, and with one exception (Sample 15) were absent from agricultural or post-agricultural soil layers. The single identification of *Carya* in Sample 15 from below mulch was not replicated in the 400x pollen counts and so is not included in the calculation of pollen concentrations. Pollen concentrations were highest in the modern surface soil samples (median 20 x 10^3 gr g^{-1}), and these samples also had the lowest percentages of degraded unidentifiable grains (median 4%). More deeply buried agricultural soil contexts have the lowest pollen concentrations (median 5 x 10^3 gr g^{-1}) and highest percentages of degraded unidentifiable grains (median 14%).

Table C.2. Pollen taxa counts identified by standard (400x) microscopy.

Common name	Genus	Count
Unidentified		
Degraded		428
Unknown		27
Exotics		
Pecan	*Carya*	X[1]
Russian Olive type	*Elaegnaceae*	1
Weedy annuals		
Bursage/Ragweed	*Ambrosia*	9
Sunflower Family	*Asteraceae*	476
Cheno-am	*Cheno-am*	925
Mustard Family	*Brassicaceae*	5
Buckwheat	*Eriogonum*	1
Grasses		
Grass Family	*Poaceae*	88
Large Grass	*Large Poaceae*	2
Shrubs		
Sagebrush	*Artemisia*	40
Mormon Tea	*Ephedra*	19
Greasewood	*Sarcobatus*	5
Arboreal		
Fir	*Abies*	11
Alder	*Alnus*	1
Juniper	*Juniperus*	622
Spruce	*Picea*	5
Pinyon type	*Pinus edulis*	1123
Pine type	*Pinus ponderosa*	511
Gambel Oak	*Quercus*	17
Succulents		
Cholla	*Cylindropuntia*	4
Prickly Pear	*Platyopuntia*	1
Other native taxa		
Spurge Family	*Euphorbiaceae*	17
Pea Family	*Fabaceae*	4
Evening Primrose	*Onagraceae*	X
Gilia Family	*Polemoniaceae*	5
Rose Family	*Rosaceae*	15
Cultigens		
Cotton	*Gossypium*	1
Maize	*Zea mays*	2

[1]X = taxa observed in 100x ISM scan but not counted during standard microscopy.

Table C.3. Poshu'Owingeh pollen counts identified by standard (400x) microscopy.

Sample	Context code[1]	Standard microscopy[2] Total tracer	Total pollen	Degraded	Exotics	Cheno-Am + *Asteraceae*	*Poaceae*	Arboreal	Cotton	Maize
1	U	79	204	23	0	58	8	109	3	0
2	A	39	311	42	0	145	9	103	1	2
3	L	86	208	30	0	72	2	95	0	0
4	A	38	263	40	0	127	9	74	1	0
5	P	43	261	32	0	100	4	113	0	0
6	P	39	328	31	0	91	2	198	0	0
7	L	73	201	23	0	32	12	123	4	0
8	L	51	291	31	0	151	2	93	3	0
9	L	201	200	26	0	99	4	53	1	0
10	M	40	493	13	0	75	8	386	0	0
11	M	58	419	21	1	68	10	307	0	0
12	L	161	114	18	0	41	3	51	1	0
13	U	74	355	19	0	99	5	219	2	2
14	U	49	304	16	0	76	4	201	10	0
15	L	76	204	28	0	68	7	86	1	0
16	U	165	227	35	0	99	1	79	0	0

[1] Codes: A = non-mulch agricultural context; L = lower mulch or sub-mulch agricultural layer; M = modern surface; U = upper gravel mulch layer; P = post-agricultural sedimentary layer

[2] *Lycopodium* tracer spike = 20484 gr in each 10 g sample

Table C.4. Cultigen concentrations identified in ISM analysis for each pollen sample from Poshu'Owingeh

Sample	Analysis level (gr g^{-1})	Cotton (ISM)	Maize (ISM)
1	1.0	30.6	0.0
2	0.9	9.1	1.8
3	0.8	0.0	0.0
4	0.9	8.6	0.0
5	0.8	0.0	0.0
6	1.0	0.0	0.0
7	0.8	32.5	0.0
8	1.0	30.8	0.0
9	0.8	7.7	0.0
10	0.7	0.0	0.0
11	0.8	0.0	0.0
12	0.9	8.9	0.0
13	0.9	18.2	1.8
14	0.8	80.7	0.0
15	0.8	8.4	0.0
16	0.7	0.0	0.0

Two domestic taxa were recovered from agricultural contexts at Poshu'Owingeh, cotton and maize, with the former being more abundant and ubiquitous. No cultigen pollen was recovered from the modern surface or post-agricultural deposits. Cotton was recovered in 2 of 2 non-mulch agricultural contexts at concentrations around 9 gr g^{-1}, and maize was recovered in one such context at a concentration around 2 gr g^{-1}. Cotton was recovered in 3 of 4 upper mulch contexts at concentrations ranging from 18 to 81 gr g^{-1}, and maize was recovered in one such context at a concentration around 2 gr g^{-1}. Cotton was recovered in 5 of 6 lower mulch contexts at concentrations ranging from 8 to 33 gr g^{-1}. No maize pollen was recovered from lower mulch contexts.

At Poshu'Owingeh, pollen samples from agricultural layers tend to have higher percentages of weedy annual taxa indicative of disturbance and somewhat lower percentages of native arboreal taxa compared to post-agricultural and modern contexts. The first category is comprised of Cheno-Ams and *Astraceae* while the second category comprises of pinyon, juniper, ponderosa pine, *Quercus* (most likely Gambel oak *Q. gambelii*), *Abies* (most likely white fir *A. concolor*), spruce (*Piceae spp.*), and *Alnus* (most likely mountain alder *A. incana tenuifolia*) in order of most to least abundant. Samples from the modern surface are lowest in weedy annuals at around 16 percent and highest in native arboreal taxa at around 76 percent. Post-agricultural layers have weedy annual pollen percentages around 33 percent, and arboreal taxa comprise around 52 percent of total pollen recovered from this context. Non-mulch agricultural contexts have around 48 percent weedy annuals and 31 percent arboreal taxa. Pollen samples from upper mulch are comprised of 25-44 percent weedy annuals, while arboreal taxa range from 35-66 percent, and samples from lower mulch are comprised of 16-52 percent weedy annuals, and arboreal taxa range from 47-61 percent. Grasses (*Poaceae spp.*) comprise around 2 percent of samples across contexts and range from 0-6 percent. Succulents (cholla and prickly pear) were identified in every context except modern at very low frequencies. Only in upper mulch (2 or 4 samples) and post-agricultural contexts (1 of 2) were cactus family pollen taxa counted at 400x in standard microscopy and in these samples constituted <1 percent of the total pollen assemblage.

Table C.5. Average pollen concentrations of major taxonomic categories by context for Poshu'Owingeh and Yunge Hills. Information for Yunge Hills is from Camilli et al. (2012: Appendix III-VI).

Site	Context	Total	Degraded	Exotics	Cheno-Am + *Asteraceae*	*Poaceae*	Arboreal	Cotton (ISM)	Maize (ISM)
Poshu' Owingeh	lower mulch	5304.2	653.7	0.0	2042.5	124.2	2197.8	14.7	0.0
	upper mulch	7796.8	566.3	0.0	2201.0	133.7	4649.1	32.4	0.5
	Non-mulch ag.	15527.0	2219.8	0.0	7359.4	487.4	4782.9	8.8	0.9
	Post-ag.	15094.0	1604.3	0.0	4856.5	150.4	8031.5	0.0	0.0
	modern	20378.0	716.2	18.0	3176.6	388.2	15576.7	0.0	0.0
Yunque	Pre-ag	4320.6	578.4	0.0	3214.6	14.4	280.7	1.0	0.0
	lower mulch	3980.7	578.4	0.5	2060.1	154.9	1149.3	1.1	0.1
	upper mulch	8072.2	357.7	4.8	3729.1	173.7	2653.7	0.9	0.3
	Non-mulch ag.	17816.0	464.7	1.0	8097.5	1077.3	7263.1	0.1	0.0
	Post ag.	18042.1	830.2	0.0	6339.7	386.4	6021.7	0.8	0.2
	modern	40658.5	702.7	2383.4	5204.9	2103.7	2451.5	0.0	0.0

Regional comparison

Absolute and relative pollen concentrations for Poshu'Owingeh were compared to a larger dataset recovered from the Yunge Hills area. At Yunge Hills, 95 pollen samples were analyzed from gravel mulched fields and associated rock alignments, hillslope terrace fields, depressions (borrow pits/basins), and surface and subsurface sediments in uncultivated or unmodified locations (Smith 2012). Because sampling for this project was coordinated with personnel who conducted the Yunge Hills project, sample contexts can be correlated between sites and directly compared. Specifically, common contexts sampled in each project include: (1)

the modern surface, (2) post-agricultural, (3) non-mulch agricultural contexts, (4) upper mulch, (5) and the lower mulch contact. In addition, the Yunge Hills study provides samples for pre-mulch soil layers (Camilli et al. 2012a, Appendix III-V). A summary of mean pollen concentrations for similar contexts is summarized in Table C.5 and illustrated in Figure C.3; complete pollen counts for all Yunge Hills samples can be found in Camilli et al. 2012a (Appendix IV).

Exotic tree taxa (hickory/pecan and Russian Olive) are recorded at concentrations two orders of magnitude higher on the modern surface at Yunge Hills compared to the same context at Poshu'Owingeh. Both sites show the same monotonic increase in total pollen concentration from pre-mulch and lower mulch to the modern surface. At Yunge Hills, degraded pollen concentrations show no apparent trend. Poshu'Owingeh diverges from Yunge Hills in this respect as degraded pollen concentrations are relatively low in mulch contexts.

At both sites, cotton pollen concentration was recovered at an order of magnitude higher than maize, and Poshu'Owingeh samples yielded far higher concentrations of cotton than Yunge Hills. At Poshu'Owingeh, gravel mulch is associated with the highest cotton concentrations of any context, with the upper mulch averaging 32 gr g^{-1}. At Yunge Hills, the upper mulch, lower mulch contact, and pre-mulch contexts average roughly 1 gr g^{-1}. At Poshu'Owingeh, contexts hypothesized to postdate the agricultural use of mulch fields are devoid of either cotton or maize pollen, while at Yunge Hills sedimentary layers postdating gravel mulch contain cotton (0.8 gr g^{-1}) and maize (0.2 gr g^{-1}). Non-mulch soil layers contemporaneous with agriculture at Yunge Hills yielded very low cotton concentrations on average (0.1 gr g^{-1}), which contrasts with Poshu'Owingeh (about 9 gr g^{-1}).

At both sites non-mulch agricultural surfaces, as well as unmodified surfaces contemporaneous with agriculture, have the highest concentrations of disturbance annuals and grasses: approximately 7,400 gr g^{-1} at Poshu'Owingeh and 8,000 gr g^{-1} at Yunge Hills. Yunge Hills and Poshu'Owingeh show diverging trends in arboreal pollen concentrations after the use of gravel much is discontinued. At Yunge Hills, tree pollen declines by 34 percent from an average of around 3,700 gr g^{-1} across agricultural layers to fewer than 2,500 gr g^{-1} on the modern surface. Across similar contexts at Poshu'Owingeh, arboreal pollen increases by about 300 percent from approximately 3,800 gr g^{-1} to 15,600 gr g^{-1}. Change in the absolute concentration of weedy annuals is the inverse of arboreal taxa at each site, with an 18 percent decline at Poshu'Owingeh and a 12 percent increase at Yunge Hills. Grasses increase at both sites in modern contexts by roughly 56 percent at Poshu'Owingeh and 350 percent at Yunge Hills. Differences in total pollen concentration across contexts have some effect on the apparent vegetation trends outlined above (Figure C.4). On a relative basis, both sites witnessed a monotonic decline in weedy annuals from agricultural contexts to modern contexts, and the increase in grasses in modern samples at Yunge Hills is much less dramatic. At Poshu'Owingeh, relative concentrations of arboreal pollen in post-agricultural contexts is close to agricultural contexts suggesting that the increase observed in arboreal pollen is very recent. This is supported by observing that modern contexts have an order of magnitude increase in the concentration of juniper pollen.

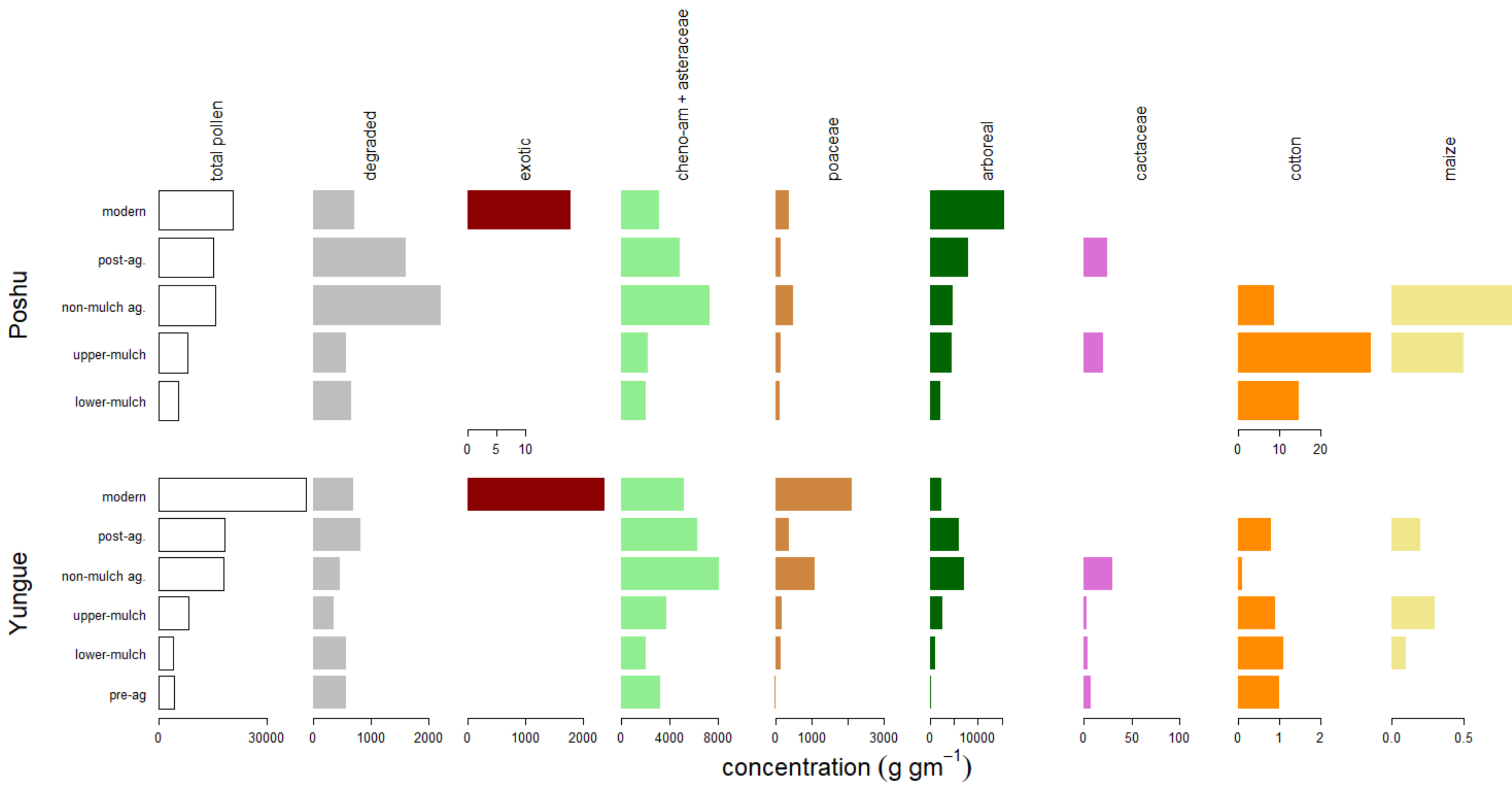

Figure C.3. Mean concentrations (gr g^{-1}) of pollen taxa from different plant functional groups and cultivars in various depositional contexts (x-axis) from Poshu'Owingeh (reported in this study) and from runoff irrigation facilities in the Yunge Hills area of Ohkay'Owingeh pueblo (Smith 2012).

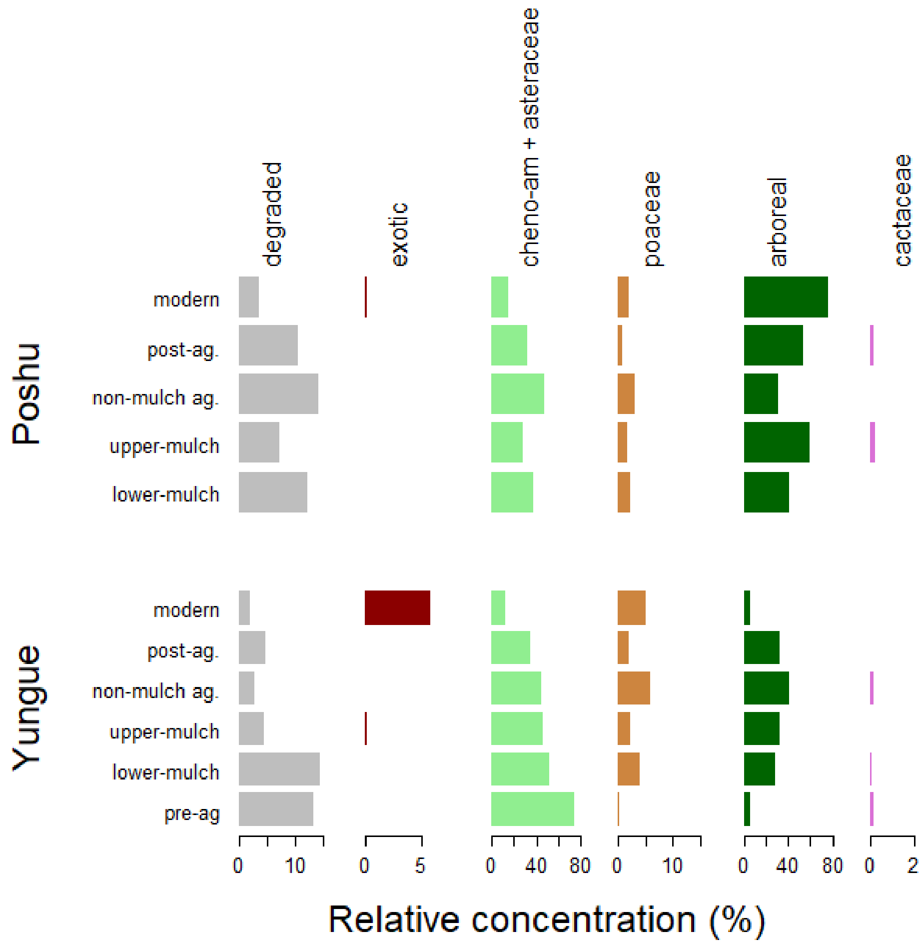

Figure C.4. Percentages of pollen taxa from different plant functional groups and cultivars in various depositional contexts (x-axis) from Poshu'Owingeh (this study) and from runoff irrigation facilities in the Yunge Hills area of Ohkay'Owingeh pueblo (Smith 2012).

Discussion

Relative intensity of cotton agriculture at Poshu'Owingeh

Cotton is insect pollinated and the working model of Smith (2012; see also Camilli et al. 2019) based on experimental data from Dean (1995) and experience at other mulch sites is that the pollen rain from flowering cotton plants is concentrated at the base of the plant. Maize is both wind and insect pollinated and can be disbursed across a wider area. Therefore, the presence of cotton pollen is an indication that a cotton plant grew in that location, whereas maize pollen suggests a local, but not necessarily immediate presence.

Comparison with Yunge Hills shows that Poshu'Owingeh cotton concentrations are indeed extremely high. The highest cotton concentrations in samples from Yunge Hills are slightly more than 15 gr g^{-1}. In a survey of data across the Northern Rio Grande region, Smith (2012) reports that cotton concentrations are typically no more than 1-2 gr g^{-1} in runoff irrigated fields of any type (Smith 2012: Table C.8). Cotton pollen is closely associated with gravel mulch and was also recovered in a water collection basin at Poshu'Owingeh. At Yunge Hills, cotton pollen is associated with gravel mulch, but is distributed over a variety of surfaces, some of which probably predate and postdate the gravel mulch fields documented in that study. At Yunge Hills, the ratio of cotton to maize in mulched fields is roughly 3:1, but at Poshu'Owingeh the ratio is about 19:1. The large difference between mean concentrations at the sites persists even after removing the sample yielding 80 gr g^{-1} from the Poshu'Owingeh dataset. Concentrations of >30 gr g^{-1} in 3 of 12 agricultural contexts are higher than any other cotton pollen density recorded in the Northern Rio Grande.

At Yunge Hills, weedy annual pollen concentrations are roughly 10 percent higher across agricultural contexts compared to Poshu'Owingeh. The ubiquities and richness of other potentially cultivated and encouraged plant families – gourd (*Cucurbita*), mustard (*Brassicaceae*), buckwheat (*Eriogonum*), mallow (*Sphaeralcea*), and purslane (*Plantago*) – suggests that crops might have been more diverse at Yunge Hills compared to Poshu'Owingeh. At Yunge Hills, taxa from this group occur in 16 of 51 (31%) gravel mulch contexts. This compares to 4 of 11 (36%) mulch contexts at Poshu'Owingeh. While the ubiquity of pollen in this general class is similar between sites, the richness of cultivated wild plants was substantially higher at Yunge Hills (only mustard and buckwheat are accounted for from this list at Poshu'Owingeh). These and other plants with a similar phenology were crucial resources in human managed ecosystems and are encouraged in traditional agroecosystems throughout the Southwest (Ford 1968; Nabhan 1982). These data suggest that gravel mulch and runoff irrigation in general may have been more focused on cotton production and a narrower range of encouraged ruderals at Poshu'Owingeh than at Yunge Hills. A variety of useful or edible wild ruderals could colonize fallow fields and contribute to the pollen assemblages recorded in this study. The resting of land is a crucial concept in contemporary Tewa agroecology, and is considered by some to be a hallmark of Ancestral Tewa land use (Duwe and Anschuetz 2013: Note 2). This model is supported in the pollen assemblage from Yunge, but less so at Poshu'Owingeh where a low diversity of ruderals and high concentrations of cotton suggest significantly reduced fallowing than at Yunge.

Comparability and quality of the pollen records

The order of magnitude difference between Poshu'Owingeh and Yunge Hills cotton concentrations cannot be explained by differential preservation or differences in sampling protocol (both projects involved identical tactics, many of the same field personnel, and analyst). At both sites, pollen samples are well preserved, with very little mixing of recent pollen into agricultural layers. The relative concentrations of degraded grains (Figure C.4) follow similar trends at Poshu'Owingeh and Yunge Hills, suggesting that the conditions of pollen preservation are similar at both locations.

Pollen records at each site are also sensitive to the unique history of population and land use change, reinforcing the conclusion that the pollen records at these two sites accurately reflect vegetation changes. Yunge Hills agricultural fields were in use from Biscuit A Black-on-white times (late 14th century A.D.) until well into the Spanish Colonial period, with the heaviest use probably in the middle 16th century, based on the frequencies of Black-on-cream pottery and historical records (Camilli et al. 2012b). After the introduction of acequia technology, runoff irrigation declined precipitously (Ortiz 1969), which would date the end of mulch field use to the 17th century. The increase in population density after the beginning of the 17th century in the Española Basin probably correlates to the decline of arboreal taxa observed in the post-mulch sedimentary layers at Yunge Hills, which is concomitant with the decline in disturbance taxa as old-field vegetation communities matured. Based on the range of tree-ring cutting dates, the abundance of Biscuit B Black-on-white pottery, and the scarcity of Sankawi Black-on-cream at Poshu'Owingeh, the disuse of gravel mulch agriculture there probably corresponds to the large population reduction after the middle 16th century throughout the Chama Basin (Ramenofsky and Feathers 2002). This corresponds to a similar decline in the abundance of disturbance taxa observed at Yunge Hills, but very low local population densities around Poshu'Owingeh allowed tree taxa to recover. The abrupt increase in arboreal taxa at Poshu'Owingeh is driven primarily by *Juniperus spp.* pollen and is likely a result of recent shrub encroachment (Davis and Turner 1986).

Social dimensions of agricultural intensification

If the increase in cotton pollen at Poshu'Owingeh is a result of decreased fallow periods or increased plant density, this would indicate that cotton was not grown simply as a supplemental product but was the focus of considerable energy. Hill's (1998:291) model for cotton specialization in the Rio Abajo suggests that cotton was grown in order to participate in exchange networks and predicts a near monoculture of cotton in specific runoff irrigation facilities on landforms above floodwater irrigated maize fields. The data recovered from Poshu'Owingeh conform to this expectation; runoff irrigation facilities are associated primarily with cotton. This could indicate intensive cotton production in the Rio Chama Basin, and could be a proxy for opportunities for inter and intraregional exchange between ca. A.D. 1400-1550 compared to later periods.

The implication is that after A.D. 1550, the importance of cotton in exchange networks decreased, possibly as a result of European disruption of populations and social networks, and later as a result of Colonial tribute demands that emphasized wool over cotton (Webster 1997). Questions remain about the apparent intensity of cotton production at Poshu'Owingeh. It is not clear whether such practices could have been maintained sustainably. No evidence for long-term fertility reduction were observed in gravel mulched fields compared to unmodified locations, but it is unclear if this is reflective of past conditions (Appendix B). It is also unclear as how widespread cotton intensification might have been throughout the Chama Basin. Current data suggest that cotton production in the Abiquiu area, the Rio del Oso, and the Rio Ojo Caliente was not as intense as at Poshu'Owingeh; however, studies such as the one undertaken here and previously at San Idelfonso and Yunge Hills need to be replicated at other large pueblos in the Rio Chama.

Why did cotton production intensify in the Rio Chama basin after about A.D. 1400? Local changes in fiber and textile production may signal broader changes in society. Production of household and trade goods have been linked to social organization and power, and historically, agricultural change has occurred synchronously with the growth of trade networks, enlargement of the economy, craft specialization, population growth, and urbanization

(McCorriston 1997). Fiber and textile production may be particularly sensitive to change because of the special link between the social and environmental context of production. Specifically, rapid adoption of new technologies and environmental change can create opportunities for fiber crop production, and rearrangements of social networks can change the landscape of supply and demand that affect decisions to adopt, abandon, or intensify non-subsistence production (Brite and Marston 2013). In the Southwest, intensification of subsistence and non-subsistence production has been widely interpreted as a socioecological response to population pressure on resources (Cordell and Plog 1979), an interpretation – with elaboration – that has proved useful for diverse interpretations of economic change and population history throughout the Southwest (Kohler 1992, 1993; Peeples et al. 2006; Stone and Downum 1996).

Anthropological analyses have identified multiple causes of intensification in archaeological and historical cases: demographic increase, social production (including exchange), risk mitigation, or a myriad of other factors (Johnston 2003; Morrison 1994; Stone 1996). The general driver of these factors is population pressure on resources. McGuire (1984) discusses proximal sources of resource population pressure or demand on production: population pressure on land and social demands for increased production. The discussion of cotton production intensification at Poshu'Owingeh suggests that it represents an example of both infrastructural intensification and classical Boserupian labor intensification. Boserup's (1965) model for intensification postulates that agricultural yield in preindustrial systems is raised by increasing land use intensity (reduced fallow) which increases labor inputs with marginally increasing costs (lowering labor efficiency as yields increase). Infrastructure based intensification raises production concentration without necessarily lowering labor efficiency (Stone 1996: 31 and references therein). At Poshu'Owingeh, the investment in gravel mulched fields is an infrastructural intensification and the hypothetical decrease in fallowing would represent a labor intensification.

There are many parallels between the process of intensification – its motivation, historical trajectory, and social effects – and diverse lines of evidence from the archaeological record in the NRG. Intensification is directed toward the goal of improving surplus production for a variety of reasons directly related to quality of life and economic security (Brookfield 2001). The Classic period in the Tewa Basin is argued by some to have coincided with increased living standards and a reduction in conflict (Kohler et al. 2014; Ortman 2016). Agricultural features associated with infrastructural intensification need not have been constructed immediately with pooled labor but could be (and usually are) assembled over long periods of time by individual acts of construction and maintenance (Doolittle 1992). As Morrison et al. (1996) indicate, social institutions, particularly religious institutions, have actively structured the historical pattern of infrastructural expansion in different case studies. In the NRG, the proliferation of systemically placed shrines and ritual spaces within runoff irrigation field complexes suggests that aspects of field construction and operation were cosmologically structured (Fowles 2009; Duwe 2016). Where labor and infrastructural costs are too high, and no technological solution is available, social responses to increasing production demands include abandonment and territorial competition to preserve or increase access to land (Stone 1996; 1997 Stone and Downum 1999). Expansion in the NRG reached its peak areal extent by the turn of the 15th century. One hundred years later, in the 16th century, population decline had begun in the NRG and population centers were contracting in settlements around the Rio Grande (Hill et al. 2004).

Conclusions

This report documents high concentrations of cotton pollen (up to 80 gr g^{-1}) in direct association with runoff irrigation features, particularly gravel mulch at Poshu'Owingeh, an Ancestral Tewa pueblo in the North Rio Grande. Prior to this study, the only evidence for cotton cultivation at Poshu'Owingeh was indirect archaeological evidence in the form of loom anchors and spindle whorls recovered from early 20th century excavations in room blocks (Jeançon 1923: 62; Plate 49). The results suggest that cotton production was important in the Chama Basin perhaps as early as the middle 14th century. Cotton fossil pollen concentrations are much higher at Poshu'Owingeh than fields at Yunge Hills, a site that overlaps temporally but whose peak occupation probably postdates Poshu'Owingeh. Similar preservation levels and the coherency of vegetation change and population history at each site support the accuracy and comparability of the two pollen records. If pollen concentrations faithfully record the relative density and duration of cotton agriculture at each site, it must be concluded that far more cotton was grown per unit of field area at Poshu'Owingeh compared to Yunge Hills. The concentrations of cotton and the diversity of ruderal plant species at the two sites suggest that gravel mulch agriculture at Poshu'Owingeh was more specialized in growing cotton relative to maize and wild cultivars compared to Yunge Hills. The implication is that more intensive agriculture characterized production at Poshu'Owingeh. If this is generally true for other early and middle Classic sites in the Rio Chama Basin, it suggests that the economic importance of cotton agriculture may have been high before the middle 15th century. A subsequent decline in cotton concentrations could signal a general decrease in the importance of cotton agriculture after the middle 16th century. Intensification at Poshu'Owingeh suggests that opportunities for exchange may have been more frequent and reliable prior to ca. A.D.1550. A full appraisal of the implications of this hypothesis is beyond the scope of this article, but agricultural change reconstructed in this study broadly coincides with the decline in Indigenous population and the instability of regional social networks caused by the 16th century invasion of Europeans. The data needed to test this hypothesis would involve more paleobotanical research and direct numerical dating of precontact agricultural sites in the region.

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